Honeywell

# Weather Avoidance Using Route Optimization as a Decision Aid: An AWIN Topical Study

Final Report
November 23, 1999

Prepared for:
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Under Cooperative Agreement No. NCC-1-291
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## Table of Contents

# Foreward

This is the final report prepared under Cooperative Agreement NCC-1-291. It covers work performed from July 1998 through November 1999 under an AWIN Topical Study: "Weather Avoidance Using Route Optimization as a Decision Aid". Dr. Kara Latorella of NASA Langley served as the Technical Monitor. Major contributors to this effort from Honeywell's Technology Center were:

- Principal Investigator: Ms. Jennifer Sly (July 1998 until August 1999) and then Mr. Gary Hartmann
- User Interface Design and Implementation: Ms. Thea Feyereisen, Dr. Vic Riley, Dr. William Rogers, Mr. Chris Misiak and Mr. Fred Wagener
- Route Optimizer Design and Implementation: Mr. Robert Schultz and Mr. Don Shaner
- Software Integration and Testing: Mr. Stephen Pratt

# 1.0 Introduction and Summary

The aviation community is faced with reducing the fatal aircraft accident rate by 80 percent within 10 years with ever increasing traffic and a changing National Airspace System. Weather is a factor in 30% of aviation accidents. By supplying more relevant weather information in a human-centered format along with the tools to generate flight plans around weather, aircraft exposure to weather hazards can be reduced.

During 1998-99, the Honeywell Technology Center conducted a topical study, "Weather Avoidance Using Route Optimization as a Decision Aid" under Cooperative Agreement NCC-1-291 with the NASA Langley Research Center. This program directly supported the NASA's five year investment areas of Strategic Weather Information and Weather Operations (simulation/hazard characterization and crew/dispatch/ATChazard monitoring, display, and decision support) (NASA Aeronautics Safety Investment Strategy: Weather Investment Recommendations, April 15, 1997).

This topical study consisted of two phases. Phase I was conducted from August 1998 through December 1998 and defined weather data requirements, lateral routing algorithms, and conceptual displays for a user-centered design. A Phase 1 Report was published in December 1998 [ref. 1]. The second phase ran from January 1999 through November 1999 and integrated vertical routing into the lateral optimizer, combined the graphical user interface with the route optimizer software, and evalued the resulting decision aid with a set of dispatchers and pilots.

The deliverables under this phase of the Cooperative Agreement consisted of a final oral presentation, the object code of the AWIN Decision Aid, and a final report. This document is the final report; it describes the design and evaluation of the AWIN Decision Aid developed under this program

## *1.1 Program Objectives*

The goal of this program is to use route optimization and user interface technologies to develop a prototype decision aid for dispatchers and pilots. This decision aid will suggest possible fligth plans around single or multiple weather hazards and present weather information with a human-centered design. A prototype of the decision aid will be developed and evaluated. The evaluation will obtain feedback from dispatchers and pilots regarding the potential benefits of this decision aid. This information will be used for follow-on work ultimately leading to a commercial product for dispatchers and/or pilots.

The following issues were addressed during the course of this study:

- Determine of how weather hazards are identified in partnership with experts, and prioritized for aircraft routing.
- Develop a route optimizer based on a cost function approach
- Document display format requirements for representing weather hazards in a route planning aid.
- Develop a static representation of display layouts suitable for an integrated planning function

Flight planning is a complex task because of the number of dynamic world models it tries to encompass and optimize. Because the underlying models and assumptions made in an automated system may be incomplete and fallible, a "cooperative" rather than "automated" flight planner has been suggested (Layton 1994). A strategic planning and replanning flight optimization tool produces a flight plan that describes at what altitude, speed, and track an aircraft will fly during various flight phases. This route determination results from a trade-off of many factors including speed, fuel efficiency, passenger comfort, arrival time, air traffic congestion, favorable forecast weather (e.g., winds aloft), forecast weather hazards (e.g., turbulence, convection, icing, volcanic activity, ozone concentration), airport or runway closures, medical emergencies, overflight fees, etc. The goal of this program was to develop a tool for dispatchers and pilots that assists in the complex problem solving task of flight planning and replanning around weather hazards in a collaborative fashion where automation, dispatch, and pilots work towards an optimal solution while maintaining passenger comfort and flight safety. This tool could be used by dispatch, air traffic control, or pilots that would clearly identify the weather hazards and their potential impact on the safety of the flight. The route optimizer would optimize the route to avoid hazardous weather and allow the pilot a "What if?" scenario capability to evaluate operating costs, time costs, and safety costs.

## *1.2 Technical Approach*

Our approach combined our human centered design expertise and route optimization technology to create such a decision aid. In partnership with weather experts, we created an integrated program with three strong domains. Figure 1-1 shows the three areas this topical study addressed in order to develop the route optimizer decision aid.

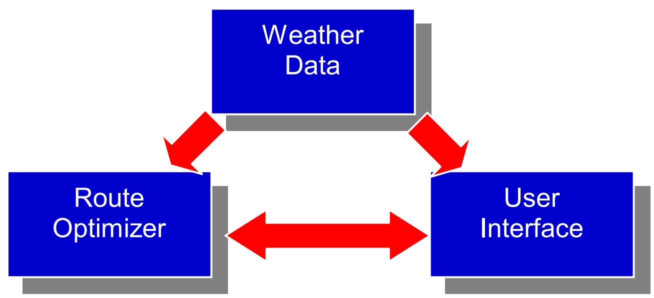


**Figure 1-1 Three Components of AWIN Program**

The first stage of our program involved visiting and interviewing experts in the field of weather. We visited a Flight Service Station, Kavouras, Northwest Airlines, and the National Center for Atmospheric Research (NCAR). We also interviewed an aviation weather consultant, Dr. Wayne Sand, and a corporate pilot. We established the working environment of different stakeholders of weather routing and examined state-of-the-art weather products.

The second part of our program generated user requirements from our field visits and synthesized these requirements into conceptual display layouts. These display layouts were integrated with the route optimizer being developed in parallel. The Route Optimizer addressed the issues of representing weather hazards is a form suitable for optimization and resulted in a practical algorithm for use in the decision Aid prototype. Finally, we designed an experiment to evaluate the suitability of the resulting decision aid. Our test subjetcs included airline dispatchers and airline and corporate pilots.

## *1.3 Operational Concept for Weather Avoidance*

Creating a flight trajectory, especially a trajectory avoiding weather, is a complex task. A dispatcher or pilot must consider safety and at the same time consider factors that affect the individual flight plus the optimization of the entire fleet of aircraft. Through our visits and interviews, we compiled a list of factors that affect a user's decision making process when making routing decisions around weather. Figure 1-2 is a summary of these factors.

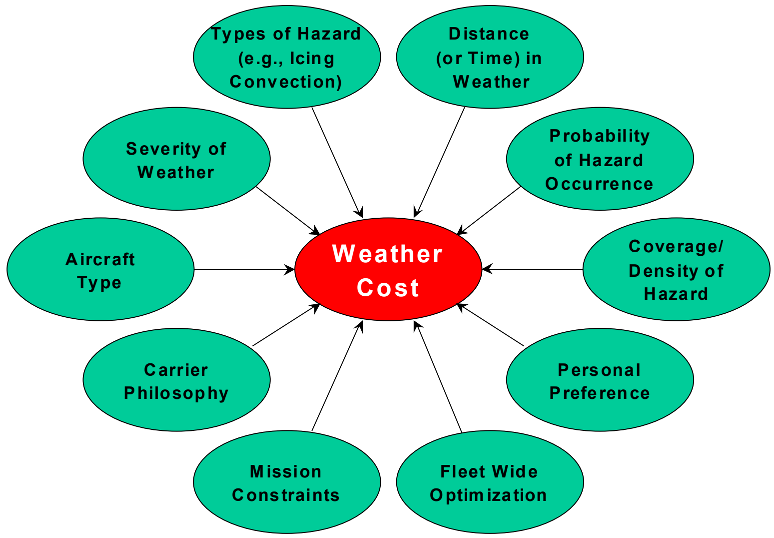


**Figure 1-2 Factors Affecting Weather Routing Decisions**

Flight optimization creates the “best” flight trajectory by minimizing the “cost” of multiple factors.

Today, many flight planning systems optimize for factors fuel or time based on a “cost index” that converts both fuel and time into the same unit: money. For this program, we wanted to add weather avoidance to the trajectory optimization formulation.

Weather data requirements were derived from discussions with various flight planners and our background in computing optimal trajectories. This analysis identified two major requirements that are important in representing weather hazards for use by an automated route optimizer:

- It is important to the user that the hazard model incorporate the movement of weather over time.
- The underlying mathematical algorithm needs a precise definition of whether a trajectory is “inside” or “outside” of the weather hazard. This requirement was satisfied by using a three dimensional polyhedron (or so-called polygon) instead of gridded point as a “no-fly” zone.

A decision aid that uses discrete fly or no fly zones offers several advantages:

- Direct manipulation of the weather hazard boundaries provides the user complete control over the behavior of the optimizer.
- Using visible boundaries around weather hazards, implies the user’s situational awareness of the routing “decisions” the route optimizer makes to avoid weather.

- The experience gained on one flight can be applied to other flights.

Figure 1-3 is a top-level diagram that illustrates the functions and dat flow and function for weather avoidance routing decisions. This concept was used during this program to develop the details of our user interface and route optimization algorithms.

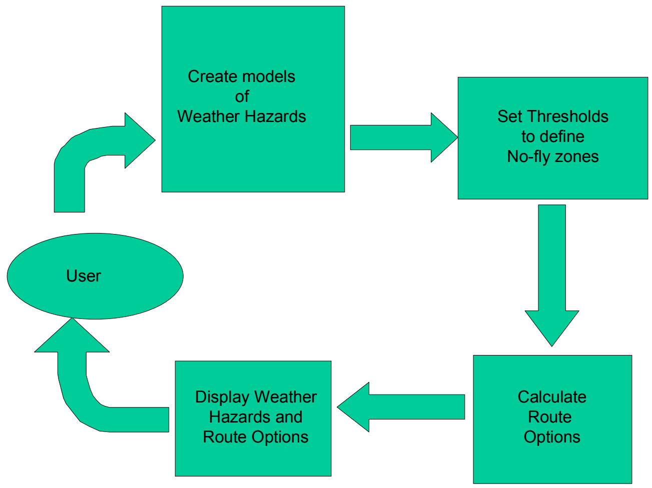


**Figure 1-3. Operational Concept**

## *1.4 Summary*

Summary comments are provides in the following three areas:

- Technical Advancement – This effort lead to a practical algorithm for route optimization and hazard avoidance. This decision aid is supported by a graphical user interface. The user interface introduced several new features such as a world view, a vertical profile, and animation that received good usability ratings.

- Need for Further Enhancements – Feedback from the evaluators indicated the need to generate a flight plan that can be "filed and flown". There were also comments indicating that the present decision aid should be extended to the terminal area.

- Next Steps – Integrating weather with flight planning was an important first step on the path to collaborative air-ground decision making. The current decision has product potential and several initiatives are exploring product options. Further development and demonstration of benefits in an operational setting is warranted based on the results of this study.

# 2.0 Modeling Weather Hazards

Our approach to modeling weather hazards involved three steps: First we considered the requirements of the decision aid. Next, we used a series of interviews with weather experts and airlines to select the weather hazards appropriate for our application; and, finally, we evaluated state-of –the-art weather products for the needs of our program. Our trip reports to various weather providers and users are summarized in our Phase 1 report [ref. 1]. The following section summarizes the weather hazards selected for use in our decision aid along with the rationale.

## *2.1 Issues in Using Weather Data*

The following issues were considered:

**Strategic flight planning –** Our route optimizer is designed as a “strategic” planner. The route optimizer uses a grid size that is proportional to the length of the flight. The current use of our grid size is not suited for high-resolution navigation. For instance, it would not be able to fly from coast to coast *and* pick its way through convective cells one mile in diameter.

**International operations –** Sources of available weather differ with location. Domestically, weather is available through multiple sources in the CONUS region. Internationally, especially in oceanic regions, much less weather information is available. We would like to address the weather needs for flight planning where less than the full complement of weather is available.

**Forecasted weather data** – Because our route planner is strategic, we need data that not only provides information on the current location of weather, but data that will also indicate where the weather will be in the future.

**Integrated sensor data** – It is vital to recognize that simply providing more weather information to operators won’t adequately support effective decision making to deal safely with weather hazards. We want to support the use of a weather product that would integrate multiple sources of information such as radar, surface observations, satellite imagery, etc. to clearly define the location and severity of the weather hazards.

**Enroute phase of flight** – Different phases of flight encounter different weather hazards. For instance, microbursts greatly affect performance in lower altitudes and usually in the take-off or landing of an aircraft. Because our program in focusing on a strategic route planner, we decided to prioritize weather hazards that occur in the en route, or cruise, phase of flight.

## *2.2 Weather Hazard Categorization*

We asked aviation weather experts to list weather hazards to aircraft, leading with the most severe hazards first. Table 2-1 contains a summary of this data.

**Table 2-1. Prioritization of Weather Hazards by Weather Experts**

| **Dr. Wayne Sand** Aviation Weather Consultant | **American Airlines** | **Northwest Airlines** | **NCAR** |
|---|---|---|---|
| 1. Thunderstorms<br>2. Turbulence<br>3. Icing | 1. Turbulence<br>2. Icing<br>3. Volcanic Ash<br>4. Convective | 1. Convection<br>2. Snowstorm/Icing<br>3. Turbulence<br>4. Volcanic Ash<br>5. Ozone | 1. Convection<br>2. Turbulence<br>3. Icing |

The relative importance of each hazard varies among operators, dependent upon operating philosophy and other factors as described in Section 1 (see Figure 1-2).

The next section describes each of the major hazards, the specific dangers aircraft face when encountering these hazards, and how these hazards are measured and quantified using intensity levels.

## *2.3 Hazard Descriptions*

**Convective Weather**

Thunderstorms can contain some of the most dangerous weather elements including turbulence, hail, and icing. A recent incident in May 1998 involving a DC-9 operated by AirTran Airlines Inc. demonstrates what can happen when an aircraft tries to skirt too close to thunderstorm cells: hail shattered three front windshields, the radome was battered off the nose of the aircraft, and severe damage was inflicted to all leading edges, engine cowlings, and fans, necessitating an emergency landing. Turbulence associated with the encounter also resulted in two injuries, one of which was serious. (Accident Synopsis DCA98MA045 "Scheduled 14 CFR 121 operation of AirTran Airlines, INC" National Transportation and Safety Board Report, May 1998.) In addition to safety concerns, convective weather impacts air traffic delays. During the warm season, at least half of the national airspace system delays are caused by aircraft attempting to avoid thunderstorms (FAA Aviation Weather Research, **http://www.faa.gov/aua/awr/prodprog.htm**). Improvements in the ability to forecast convective weather coupled with the integration of this information in a flight planning tool that optimizes around the convective activity (or other hazard areas) will benefit users by increasing separation from convective weather and reducing air traffic delays by better planning before the aircraft is even airborne.

Some of the challenges in the routing around convective activity include attenuation, blocked or inoperative signals, lifetimes of cells, hazard being different from radar reflectivity, and transoceanic availability of relevant information. Attenuation of the signal, where the signal becomes weakened because it is absorbed, scattered, or reflected along its path, can make it difficult to see the targets in the background (e.g., in the air this means that cells behind the cell in front of you may not be displayed). The signal can also be blocked by mountainous terrain, or stations may simply become inoperative at various times. Because of the instability of convective activity, storms can mature and dissipate in less than an hour. Although radar returns are available every 5 minutes, the weather radar summary chart (with interpretations) is available only hourly from the NWS and the thunderstorm timeframe can be shorter than the time between hourly radar summary charts.

Currently, weather radar is the primary tool used to detect thunderstorms. The Next Generation Weather Radar system (NEXRAD) is capable of measuring winds out to 60nm and weather features to 130nm. A radar reflectivity intensity scale or VIP scale is used as an indication of precipitation rate. This scale is shown in the table below.

### Table 2-2 Video Integrator Processor (VIP) Intensity Levels for Liquid Precipitation
**(Adapted from FAA AC 00-45D)**

| VIP Level | Precipitation Intensity | Rainfall Rate In/hr Stratiform | Rainfall Rate In/hr Convective |
|---|---|---|---|
| 1 | Weak | < 0.1 | < 0.2 |
| 2 | Moderate | 0.1 – 0.5 | 0.2 – 1.1 |
| 3 | Strong | 0.5 – 1.0 | 1.1 – 2.2 |
| 4 | Very strong | 1.0 – 2.0 | 2.2 – 4.5 |
| 5 | Intense | 2.0 – 5.0 | 4.5 – 7.1 |
| 6 | Extreme | > 5.0 | > 7.1 |

Radar provides composite reflectivity data that are not necessarily consistent with the associated weather hazard phenomenon; a displaced gust front, hail, and severe turbulence may exist well outside the storm cloud. Additionally, radar is not available over the water so convective activity must be interpreted from satellite images.

Pilots will elect to fly through (and dispatcher will route through) an area of known convective activity if it is felt that they can "pick their way through it," i.e., perform lateral deviations around the individual cells. However, if the coverage is dense, they may elect to circumnavigate the whole area. The table below defines the commonly used terms in describing thunderstorm coverage.

### Table 2-3 Area Coverage for Convection
**(Adapted from FAA AC 00-45D)**

| Adjective | Coverage |
|---|---|
| Isolated | Single cells (no percentage) |
| Widely scattered | Less than 25% of area affected |
| Scattered | 25 to 54% of area affected |
| Numerous | 55% or more of area affected |

In addition to coverage, an area of convective weather may be circumnavigated. Table 3-4 is a chart defining the terms used to describe probability of convective activity occurring.

### Table 2-4 Variability Terms
**(Adapted from FAA AC 00-45D)**

| Term | Description |
|---|---|
| Occasional | Greater than 50% probability of the phenomenon occurring but for less than 1/2 of the forecast period |
| Chance | 30 to 50% probability (precipitation only) |
| Slight Chance | 10 to 20% probability (precipitation only) |

## Turbulence

Aircraft encounters with unexpected turbulence can be hazardous to the aircraft and passengers. For example, in 1997, there were 11 flight attendant injury reports and 6 passenger injury reports due to turbulence.

Turbulence, as reported by pilots, issued in SIGMETS, or convective SIGMETS, is reported as an intensity variable. Some levels of turbulence may be tolerable or acceptable when optimizing a flight plan. This of course depends upon the nature of the operation, e.g., cargo airlines may accept a higher level of tolerable turbulence to fly through than an airline concerned about passenger comfort and safety. However there is a level of turbulence that is unacceptable to fly through because it may cause structural damage and/or loss of flight control. The table below describes the turbulence intensity reporting descriptions along with associated effects on passengers and the aircraft.

## Table 2-5 Turbulence Reporting Criteria
(Adapted from FAA AC 00-45D)

| Intensity | Aircraft Reaction | Reaction Inside Aircraft |
|---|---|---|
| Light | Turbulence that momentarily causes slight, erratic changes in altitude and/or attitude (pitch, roll, yaw). Report as *Light Turbulence.** **or**<br>Turbulence that causes slight, rapid, and somewhat rhythmic bumpiness without appreciable changes in altitude or attitude. Report as *Light Chop.* | Occupants may feel a slight strain against belts or shoulder straps. Unsecured objects may be displaced slightly. Food service may be conducted and little or no difficulty is encountered in walking. |
| Moderate | Turbulence that is similar to Light Turbulence but of greater intensity. Changes in altitude and/or attitude occur but the aircraft remains in positive control at all times. It usually causes variations in indicated airspeed. Report as *Moderate Turbulence.** **or**<br>Turbulence that is similar to Light Chop but of greater intensity. It causes rapid bumps or jolts without appreciable changes in aircraft altitude or attitude. Report as *Moderate Chop.* | Occupants feel definite strains against seat belts or shoulder straps. Unsecured objects are dislodged. Food service and walking are difficult. |
| Severe | Turbulence that causes large, abrupt changes in altitude and/or attitude. It usually causes large variations in indicated airspeed. Aircraft may be momentarily out of control. Report as *Severe Turbulence.** | Occupants are forced violently against seat belts or shoulder straps. Unsecured objects are tossed about. Food service and walking are impossible |
| Extreme | Turbulence in which the aircraft is violently tossed about and is practically impossible to control. It may cause structural damage. Report as Extreme Turbulence.* | |
| | * High level turbulence (normally about 15,000'AGL( that is not associated with cumuliform cloudiness, including thunderstorms, should be reported as CAT (clear air turbulence) preceded by the appropriate intensity, | |
| *Reporting Term Definitions* | Occasional – less than 1/3 of the time<br>Intermittent – 1/3 to 2/3 of the time.<br>Continuous – More than 2/3 of the time. | |

### Icing

The industry continues to confront icing as a major concern to aviation safety. In-flight icing is defined as "the accretion of supercooled liquid in clouds or precipitation onto an airframe during flight" (Politovich). Icing is a factor in numerous aircraft incidents and accidents. One notable accident involving the encounter of in-flight icing occurred in October 1994 when an Avions de Transport Regional ATR-72 operated by Simmons Airlines as American Eagle flight 4184 crashed after the flight crew lost control of the airplane during an adverse roll event at 9,200 feet. The crew of four and 64 passengers were killed and the airplane destroyed. The NTSB concluded that the loss of control was caused by a sudden and unexpected aileron hinge moment reversal that occurred after a ridge of ice built up beyond the deice boots.

Aircraft icing is a major hazard to aviation because of its potential to reduce aircraft efficiency, capability, power, and responsiveness. All field visits conducted including the FSS, Kavouras, Northwest AOC, and NCAR identified icing as a major aviation weather hazard. Icing is known as a cumulative hazard because it increases weight, reduces lift, decreases thrust, and increases drag simultaneously (AC 00 –6A). If the ice accumulates on the fuselage or wing, it can disrupt airflow and thus decrease the aircraft's flying capability. If the ice accumulates near an engine air intake, it can result in a loss of power. Icing can also build up on the brakes, landing gear, aft of wingboots, and other instruments or antenna, resulting in a hazardous situation (as it did in the ATR-72 accident previously mentioned).

Icing has the potential to form on an aircraft when it flies through visible moisture (i.e., rain droplets or clouds) *and* the temperature is at the point where the moisture striking the aircraft is 0ºC or colder (Ahrens, 1988). The three types of aircraft icing have been classified as **clear**, **rime**, and **mixed**, and they have different effects on the aircraft. **Clear** ice can occur when an aircraft flies through an area of freezing rain (or in cumuliform clouds), and large supercooled drops strike the leading edge of the wing and form a thin film of water. This film of water quickly freezes and forms a smooth, solid, transparent sheet of ice. Clear ice can accumulate quickly and is most difficult for de-icing equipment to eliminate. **Rime** ice occurs when the cloud droplets freeze before they have time to spread, producing a rough, whitish brittle coat. It is lighter weight than clear ice and can be more easily removed by de-icers. The third type of icing in mixed. **Mixed** ice forms when drops are varied in size or when liquid drops are intermingled with ice particles or snow. In weather forecasts or PIREPS, icing is normally classified by type and intensity category. The following table describes the intensity levels along with associated operational effect on aircraft.

**Table 2-6 Icing Intensities, and Airframe Ice Accumulation**
**(Adapted from FAA AC 00-45D)**

| Intensity | Airframe Ice Accumulation |
|---|---|
| Trace | Ice* becomes perceptible. Rate of accumulation slightly greater than rate of sublimation. It is not hazardous even though deicing/ anti-icing equipment is not used unless encountered for an extended period of time (over one hour). |
| Light | The rate of accumulation may create a problem if flight is prolonged in this environment (over one hour). Occasional use of deicing/ anti-icing equipment removes/ prevents accumulation. It does not present a problem if the icing equipment is used. |
| Moderate | The rate of accumulation is such that even short encounters become potentially hazardous and use of deicing/ antiicing equipment or diversion is necessary. |
| Severe | The rate of accumulation is such that deicing/ anti-icing equipment fails to reduce or control the hazard. Immediate diversion is necessary. |
| | * Icing may be rime, clear and mixed. |
| Rime Ice: | Rough milky opaque ice formed by the instantaneous freezing of small supercooled water droplets |
| Clear Ice: | A glassy, clear or translucent ice formed by the relatively slow freezing of large supercooled water droplets. |
| Mixed Ice: | A combination of rime and clear ice |

### Volcanic Ash

When volcanoes erupt, they spew tons of ash particles into the atmosphere. These clouds spread downwind at an average of 600nm per day. As a pilot approaches an ash cloud, it is not always easy to distinguish them from "ordinary" clouds. For example, in December 1989, a Boeing 747-400, operated by KLM Royal Dutch Airlines as flight 867, lost all power and dropped from 25,000 to 12,000 feet in 12 minutes near Anchorage, Alaska. After 7-8 attempts to restart the engines, the crew successfully regained power. No injuries were reported, but there was extensive surface and engine damage in excess of $80 million to the aircraft. The NTSB ruled the incident an inadvertent encounter with a volcanic ash cloud. (Casadevall 1994 Hazards to aircraft flown through volcanic ash can be immediate or long term. Examples of immediate damage can include smoke and ash in the cockpit, windscreens unusable because of abrasion, and engine flameout. Long-term effects are more difficult to identify but may include damage to plastics, rubber seals, lubricants, and metal parts). Because of the immediate safety implications, the long-term hazardous effects, and the need to minimize disruption of schedules, the presence of airborne volcanic ash is an additional weather hazard that should be considered during route planning and replanning.

**Ozone Concentration**

Ozone is toxic to people and, when present in large concentrations, it can irritate the eyes and cause respiratory difficulties. Naturally occurring ozone in the stratosphere can create a hazard to flights. Usually, this higher concentration of ozone is above the altitudes that aircraft fly (with the exception of an super-sonic transport or some military aircraft). However, sometimes atmospheric conditions can draw the higher ozone concentration down to the lower altitudes where more aircraft fly. Some airlines restrict flights to lower altitudes when crossing a region of predicted ozone concentrations above a critical level. Therefore, for safety of passengers and crew, the presence of high ozone concentration is a weather hazard that should be considered during route planning and replanning.

**Weather Hazards Levels**

For this study, the following five enroute weather hazards were selected for representation in the AWIN decision aid.

- Convective Weather
- Icing
- Turbulence
- Volcanic Ash
- Ozone Concentration

In addition, a provision for a custom or “user defined” category is included.

Weather hazards can be quantified by the nature of their effect on the operation and are typically described by an associated severity index or level (ie, severe icing or moderate turbulence). The then issue becomes one of deciding how many levels are useful. Our review of various weather products indicated that many different indices are used and some experimental products contain a scaling of 1 – 100. For this decision aiding application, we determined the appropriate number of levels by considering the rationale why a dispatcher or pilot would route around a hazard. Our optimization criteria [ref. 1] identified four major criteria corresponding to comfort, company policy, regulatory or safety issues. Thus, our decision aid will model each hazard type using four levels of severity (1 through 4) indicating least severe to most severe.

## *2.5 Modeling Weather for Route Optimization*

Weather data requirements were derived from discussions with various flight planners and our background in computing optimal trajectories. This analysis identified two major requirements that are important in representing weather hazards for use by an automated route optimizer:

- It is important to the user that the hazard model incorporate the movement of weather over time.
- The underlying mathematical algorithm needs a precise definition of whether a trajectory is “inside” or “outside” of the weather hazard. This requirement was satisfied by using a three dimensional polyhedron (or so-called polygon) instead of gridded point data.

**Polygon Representation**

This section presents the details of the "moving polygon" representation developed to model weather hazards as an enclosed volume where it is not safe for the aircraft to fly.

The "no fly" volumes used by AIRWAy can be created by experienced weather forecasters or created by an automatic weather data generator and represented clearly to both the routing tool and to the user. Depending on the accuracy of the weather data, these polygons may be formulated to include safety "buffer zones" that are also "no fly" regions. Since our weather hazard polygons will be displayed using transparent colors, it is possible to also display the underlying graphical weather data. This "complementary" data would not be used by the automatic routing algorithm but it could be displayed on the AWIN GUI, clearly indicating the extent of the buffer zone associated with each polygon hazard. The use of "complementary" data was not investigated in the current program.

The weather hazard representation is a 3-D polyhedron, comprised of a 2-D convex "polygon" with top and bottom altitude limits. Figure 2-1 shows an altitude slice through the volume illustrating the fact that the top and bottom surfaces of the enclosed volume are portion of a sphere. Since any plane intersecting this volume results in a "polygon" shape, the general weather hazard model will be referred to as a "polygon".

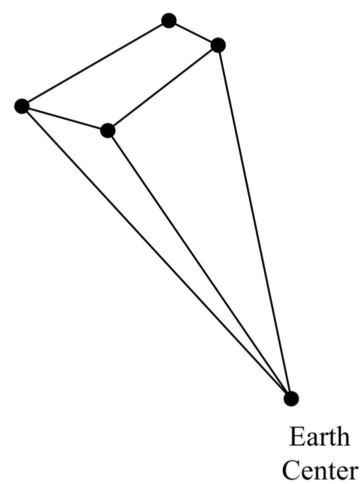


**Figure 2-1 Illustration of an Altitude Slice of the Weather Hazard**

Figure 2-2 illustrates such a "weather polygon" (five sided example). The polygon sides are vertical planes. The polygon vertices are defined in three dimensions as (latitude, longitude, altitude). Movement of the hazard is described by a vector indicating the direction of movement and speed of the center of the projection on the ground. This center is defined as the average of the 3D vectors pointing to the "N" vertices (in the example in Figure 3, N=5).

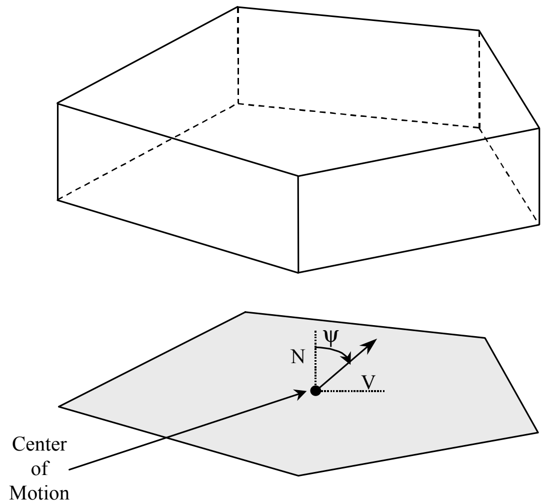


**Figure 2-2 Representation of Weather Hazard**

**Reconciliation of Polygon Hazard Model with NCAR Weather Products**

In order to verify our polygon weather model, we analyzed two data sets ontained from NCAR. The first data set was gridded convection data, covering a rectangular area which included the continental United States. The area covered was 1830 points in longitude from W130 to W60 and 918 points in latitude from N20 to N53. This gridded data was converted to a list of (latitude, longitude, intensity) triples that could then be overlayed on the "world" map of the AWIN display interface.

The second dataset was a file generated by an NCAR program which identifies polygon areas which mark significant areas of convection activity (referred to as "detection" polygons). For each of these polygons, it also produces the coordinates of the centroid, and the predicted speed and direction of motion, together with polygon coordinates at their predicted locations one hour into the future ("prediction" polygons). In the specific sample of interest, there were 25 polygons identified, each with 72 vertices. However, for each polygon, many of these vertices were duplicates which effectively reduces the complexity of the polygons. The detection and prediction polygons were converted, along with the speed and direction information, to the format used for hazards in the AWIN display interface.

Using the AWIN display interface, we displayed all of the gridded points above an intensity threshold which was adjusted so that a number of the "detection" polygons clearly outlined dense sets of points. This established that we had correctly mapped both the gridded data and polygon data to a consistent set of latitudes and longitudes.

As a test of our hazard movement model, we then took the "prediction" set of polygons, and projected them back along the direction of motion, using the AWIN display interface. The result was an exact overlay with the original gridded data and detection polygon sets from NCAR. A representative portion of this data is shown in Figure 2-3.

Together, these tests demonstrate that our weather modeling approach is compatible with weather prediction products as envisioned by NCAR

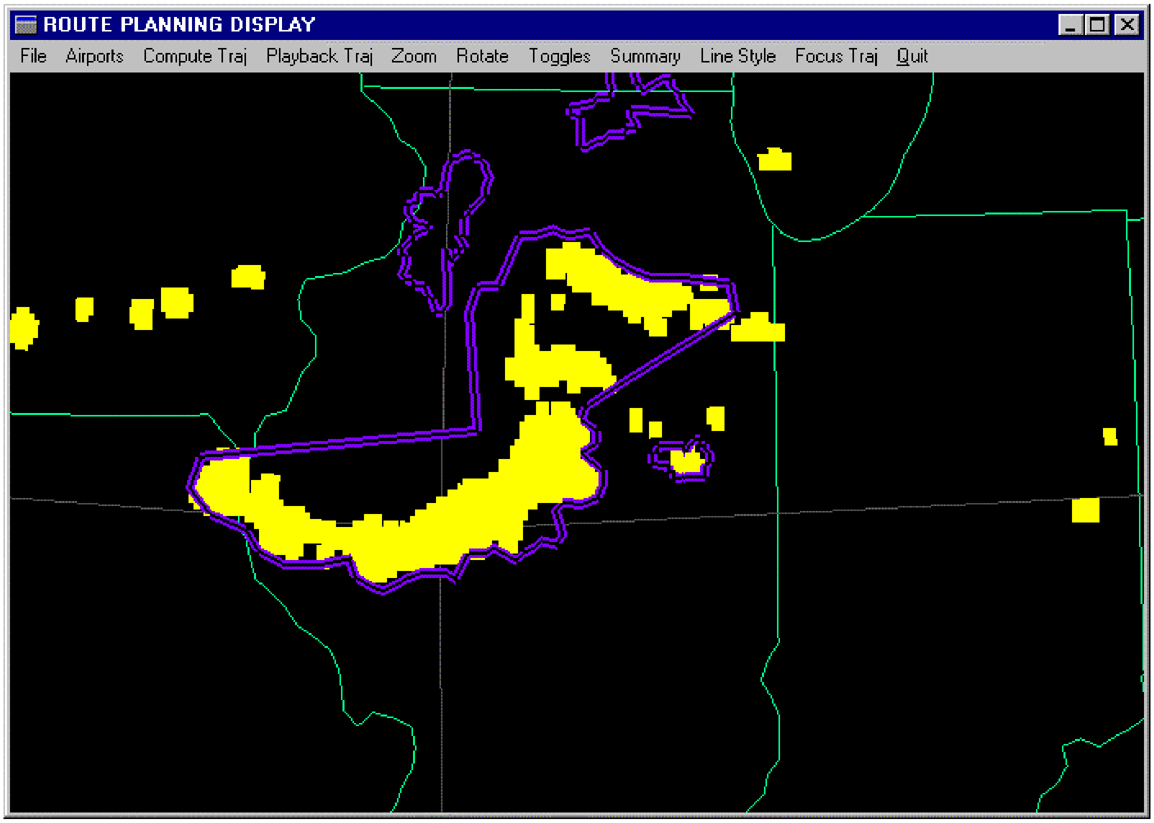


**Figure 2-3 NCAR Grided Data With Polygon Boundaries**

# 3.0 Design of the Route Optimizer

This section formulates the route optimization problem and overviews the algorithm.  Further details are contained in Appendices F, G and H.

## *3.1 Problem Formulation*

In general when planning flights the pilot or dispatcher will, in addition to minimizing fuel time and over-flight fees, want to avoid hazard region such as severe weather (convection,  turbulence, icing, etc. ), special use airspace, volcanic ash and environmentally and politically sensitive regions.  The routing geometry to avoid weather problem is illustrated in Figure 3-1.

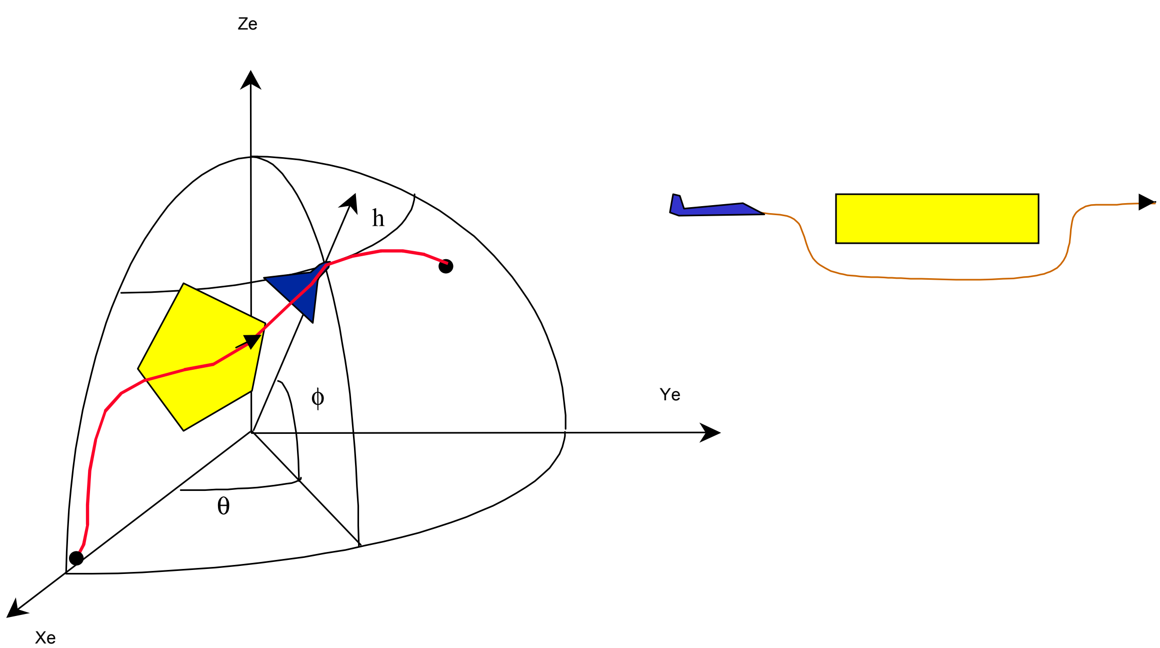


**Figure 3-1  Geometry For Route Planning**

The best route may fly around hazard regions or may fly above or below it. In summary, the problem in route optimization is to find routes that satisfy these diverse goals:

- Minimize the amount of fuel
- Meet a time or time window or minimize flight time

- Avoid severe weather regions
- Avoid other hazard regions such as special use airspace, volcanic ash,     environmently sensitive regions
- Avoid politically sensitive regions
- Reroute in flight to a nearest or desirable airport in the cases of non-normal events

### 3.2 Route Optimizer Overview

The route solver, shown in Figure3-2, computes a three-dimensional route, which minimizes a cost function. The cost function consists of fuel, time, weather costs and over-flight fees. The solution is displayed over a world map, which also has overlays of the wind field and the weather, represented in polygon form. The operator, pilot or dispatcher can interact with the route solver through the user interface. The user can select the city pair the required time of arrival, hazard weightings.

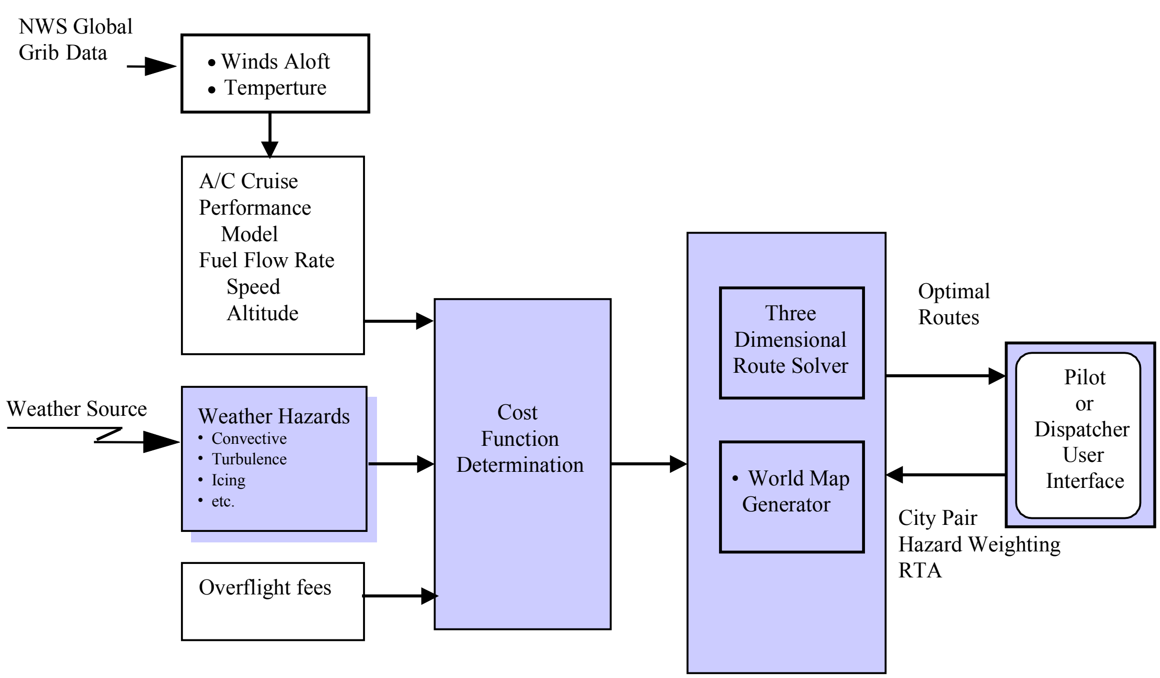


**Figure 3-2 Route Optimizer Configuration**

The processing element are:

- Pilot or dispatcher interface

- Three Dimension Route Solver,
- World Map Generation,
- Cost Function Determination,
- Weather Hazards,
- Aircraft Cruise Performance - Fuel Flow Rate and Time.

### *3.3 Weather Hazard Costs*

The weather hazard costs are the danger of flying through a severe weather region. The weather polygon moves at a fixed course and speed starting from some reference time as shown in Figure 3-3. A three dimensional representation of a weather polygon is shown in Figure 3-4

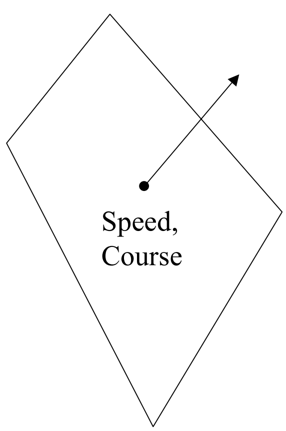


**Figure 3-3 Moving Weather**

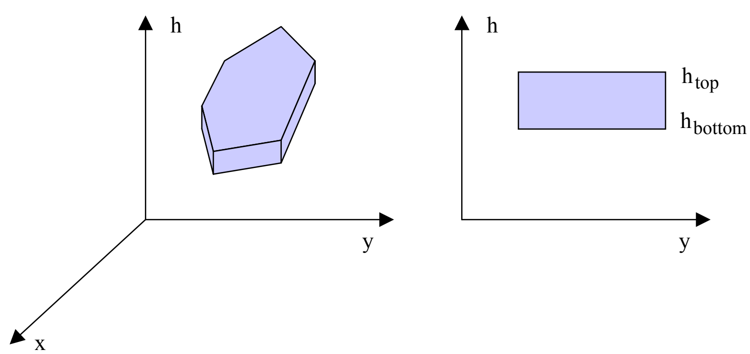


**Figure 3-4 Three Dimensional Weather**

The weather data base consists of the verticies of the polygon, speed, course, the tops and bottoms of the region, and the associated danger costs. The hazard costs depend on the danger cost of the particular cell and the distance traveled. The hazard transition costs are

$$\Delta C_{hazard} = Cost_{hazard}(\phi, \theta, h)\Delta S$$

The method of determining if the path is in the hazard is shown in Figure 3-5

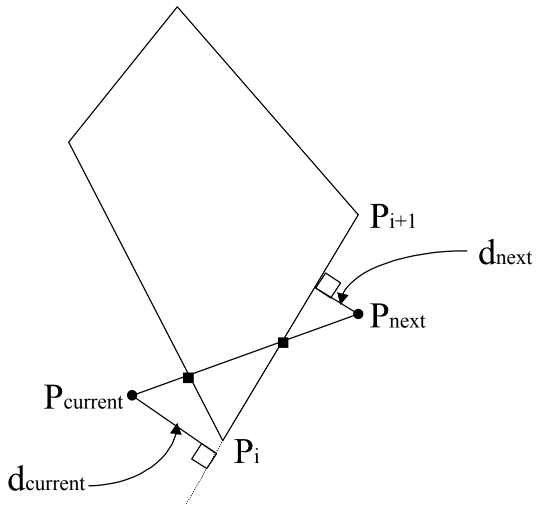


**Figure 3-5 Definition of A Weather encounter Using a Route Segment**

For each polygon segment, define $d_{next}$, $d_{current}$ corresponding to $P_{next}$,$P_{current}$.

If $d_{next}$, $d_{current}$ $< 0$ => then segment is outside, so quit

else, if $d_{next} < 0$, $d_{current} > 0$ => then clip $P_{next}$

else, if $d_{next} > 0$, $d_{current} < 0$ => then clip $P_{current}$

Upon completion, the remaining segment represents the intersection of the polygon and the original route segment

## *3.4 Aircraft Performance Model*

The fuel time and cost are determined from the aircraft optimal cruise performance conditions. In cruise the aircraft is in force equilibrium as shown in Figure 3-6. The nomenclature is given in Table 3-1.

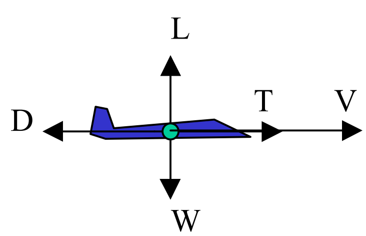


**Figure 3-6 Aircraft in Cruise**

## Table 3-1 Nomenclature

| | |
|---|---|
| $C_L$ | - coefficient of lift |
| $C_d$ | - coefficient of drag |
| CI | - cost index |
| CF | - cost function |
| C' | - curve fitting parameter |
| D | - drag |
| FFR | - fuel flow rate |
| h | - altitude |
| $h_{ref}$ | - reference altitude |
| L | - lift |
| M | - Mach number |
| sos | - speed of sond |
| $V_a$ | - air speed |
| $V_w$ | -wind speed |
| W | - weight |
| $W_f$ | - weight of fuel |
| $S_a$ | - aerodynamic reference area |
| S | - arclenght distance traveled |
| $\sigma$ | - specific fuel consumption |
| $\alpha$ | - curve fitting parameter |
| $\theta$ | - atmospheric temperature ratio |
| $\delta$ | - atmospheric pressure ratio |
| $\pi$ | - throttle |

The equations of motion for cruise are:

$$\frac{dm_f}{ds} = \frac{FFR(V_a, \pi, h)}{V_a + V_w}$$

$$\frac{ds}{dt} = V$$

$$L(V_a, \pi, C_L) - W = 0$$

$$T(V_a, \pi, h) - L(V_a, \pi, C_L) = 0$$

$$V = V_a + V_w(\phi, \theta, h)$$

In optimal cruise, the cost integral (C) in minimized.

$$C = \int_0^{S_f} \left(\frac{dm_f}{ds} + CI\frac{1}{V}\right)ds$$

The parameter CI is the ratio of cost of time (in monetary units) to the cost of fuel (in monetary units). For a small arclength step □S, the fuel, time and cost increments are:

$$\Delta Fuel = \frac{dm_f}{ds}\Delta S$$

$$\Delta t = \frac{1}{V}\Delta S$$

$$\Delta Cost_{ft} = \Delta Fuel + CI\Delta t$$

Traditionally, the fuel time cost are combined into a single cost function (CF).

$$CF = \frac{FFR + CI}{V}$$

Then

$$\Delta Cost_{ft} = CF\Delta t$$

If there are hazards, the cruise altitude may be specified, e.g., the top or bottom altitude of the hazard. In this case the optimal cruise is computed with a specified altitude. Thus, there are two possible cruise solution types: 1) unconstrained cruise - the altitude is free to be chosen during the optimization, and 2) constrained cruise - the altitude is specified. The two fuel time optimal cruise solutions are pre-computed and stored as a function of the parameters: weight, cost index and wind speed. The two types of optimal fuel time cruise solutions are:

**Fuel time Costs**

| **Altitude Not Specified** | **Altitude Specified** |
|---|---|
| $\Delta Cost_{ft} = CF(W, CI, V_w)_{h_{free}}\,\Delta S$ | $\Delta Cost_{ft} = CF(W, CI, V_w)_{h_{specified}}\,\Delta S$ |
| $h = h_{cruise}(W, CI, V_w)_{h_{free}}$ | $h = h_{specified}$ |
| $V_a = V_{cruise}(W, CI, V_w)_{h_{free}}$ | $V_a = V_{cruise}(W, CI, V_w)_{h_{specified}}$ |

### *3.5 Total Cost Function Determination*

The total cost includes fuel, time, and the hazard costs.

$$\Delta Cost = \Delta Cost_{ft} + C_h \Delta\cos t_{hazard} + \Delta\cos t_{overflight}$$

The hazard cost may or may not exist depending on whether the hazard is passed through on the transition. The fuel time costs depend on whether the altitude is free or specified say at the top or bottom of a weather cell.

Details of the solution approach are contained in three Honeywell proprietary appendices that are contained in a separate volume. The appendices are:

F. Description of Three Dimensional Route Solver Algorithm
G. Route Solver Computer Program Structure
H. Constrained Altitude Cruise Optimization

# 4.0 Design of the Graphical User Interface

This section describes the formulation of the conceptual display layouts for the flight planning and replanning decision aid. This task contained three parts:

- Define dispatch/ flightcrew weather-related decisions and information requirements,
- Determine display requirements for weather hazards, and
- Develop conceptual display formats for integrated planning.

To accomplish this goal, a user-centered requirements definition process was followed. First we learned how the tool would be used in an operational context by visiting with an FSS, Kavouras, NCAR, and NWA AOC. This helped us identify weather hazards that an aircraft would strategically route around, dispatcher responsibilities and tasks, and the determination of what information the operator would need to support decisions and tasks associated with strategic planning and replanning. The information support guidelines would drive the functionality and system requirements. Once the requirements had been formulated, conceptual static display concepts were generated. Figure 4.1 below shows the process followed in to generate display concepts.

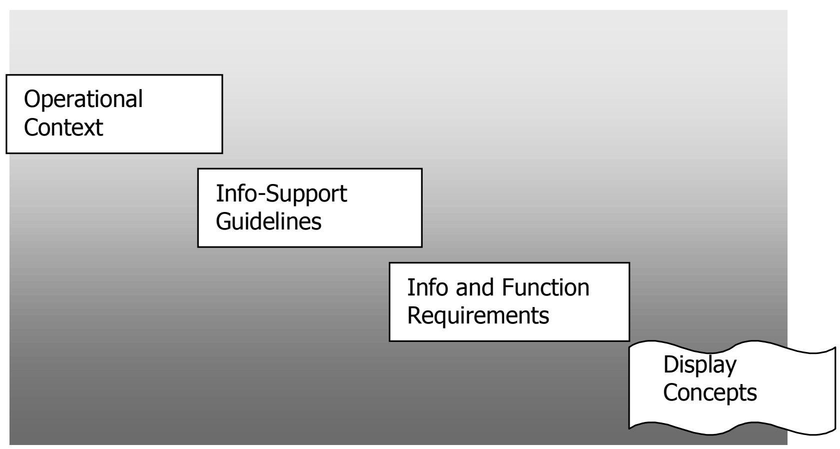


**Figure 4-1. User-centered Design Process for Building Initial Display Concepts**

## *4.1 Operational Context*

An understanding of the operational context was developed through four on-sight visits, an interview with a pilot, and review of related literature. On our visits we met with and interviewed people at a Flight Service Station, aviation weather graphics provider, an AOC, and an experimental weather product development group. In addition, we informally interviewed airline and corporate pilots. We learned more about who the users are, what their responsibilities and tasks are, and what weather-related decisions they make. We learned more about the information that is required to support their tasks, what tools or products they currently use to do their job, and in what context the tool will be used. Table 4.1 below describes the parties that were visited and an overview of the nature of their operations. Our Phase 1 report contains additional details of the trip reports [ref. 1].

## Table 4-1. Observational Fieldtrips

| Job Title | Company | Nature of Operations |
|---|---|---|
| Weather Specialist | FAA | Provide weather briefings to pilots. Assist pilots in reroute around inflight weather hazards. |
| Aviation Marketing Manager | Kavouras | Provide operationally specific aviation weather forecasts and graphic products for airlines, FSS, and corporate flight departures. |
| Meteorologist | NWA | Gather, analyze, forecast, and distribute many forms of worldwide weather data. |
| International Dispatcher | NWA | ▪ Authorize, regulate, and monitor flights according to FAA and company regulations.<br>▪ Compute fuel required for a flight according to the type of aircraft, weather conditions, fuel price differentials, and FARs.<br>▪ Monitor progress of flights and will delay or recommend cancellation of flight according to conditions.<br>▪ Adjust flight routings and altitudes to avoid hazardous weather or reduce delays. |
| Research Applications Engineer | NCAR | Conduct research on improving the ability to detect and predict aviation weather hazards and develop aviation weather products for the aviation industry and airports. |

## *4.2 Information Support Guidelines*

The dispatchers and pilots alike stressed that simply providing more weather-related information to dispatchers and flight crews would not adequately support effective decision making for routing choices. There is a plethora of weather data available, but what was needed was more context-relevant information to support strategic routing decisions. Based upon interviews, observations, and domain knowledge, a matrix was developed that identifies the weather-related decisions and tasks relevant to strategic routing. In addition to the decisions and tasks, it identifies the constraints or conditions that the decision or task is made under, the current data or sensors that support that decision, and the associated guidelines to support the information needs

Table 4.2 below lists the information-support guidelines that were generated as a result of the analysis of the weather-related tasks and decisions for strategic routing.

**Table 4-2. Information Support Guidelines**

| Weather Decision/Task | Information Support Guideline |
|---|---|
| Go/No-Go | ▪ Ability to determine minimum weather requirements are met for departure and destination<br>▪ Ability to determine that crews have enough duty time<br>▪ Ability to determine aircraft equipped properly to handle this flight in these conditions<br>▪ Ability to determine my crew is qualified to fly in these conditions |
| Alternate Requirement | ▪ Ability to determine minimum weather requirements are met for alternate |
| Fuel Requirement | ▪ Ability to determine fuel that is required to be carried on this flight |
| Planned Route and Replanned Route | ▪ Ability to plan a path that takes advantage of winds/temperature but avoids potential hazard areas that I want it to avoid (based upon threat level of hazard and may priorities of comfort, time, and efficiency whilst maintaining an acceptable safety level) |
| Build Situation Awareness | ▪ Ability to form big picture of weather (and traffic) hazards that may affect the flight |
| What if analysis? | ▪ Ability to determine consequences to time, fuel, distance, passenger comfort, and safety margins for various routes |
| Communication | ▪ Ability to share information with other interested parties about potential weather hazards and how they may affect routing of flight |

## 4.3 Information and Function Requirements

A flight planning task analysis was performed from the viewpoint of dispatcher responsibilities (including weather-related responsibilities in addition to other flight-planning related activities). The tasks required to meet those responsibilities, the system functions required to support those tasks, and the information requirements to support the functions were all identified. The product from this task analysis is a description of the functions that routing tool would have to support along with a listing of the information requirements for a dispatcher routing tool.

Figure 4.2 below shows the overall HCD analysis process. The task analysis and resultant requirements can be found in Appendix C of Reference 1. The bolded arrows depict the main information and function requirements process analysis path taken. A discussion of some of the resultant highlights that may not seem obvious to someone without doing the analysis that our optimizer will attempt to support follows.

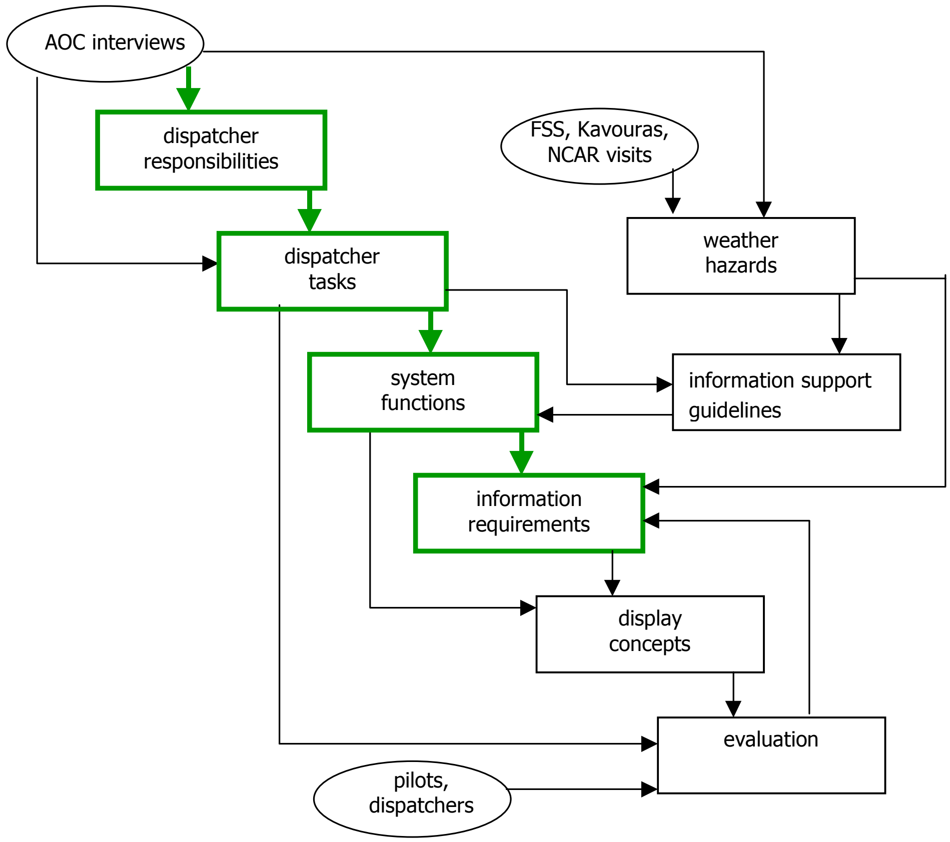


**Figure 4-2. Information and Function Requirements Process**

**Optimization Hierarchy**

It was identified that operational tradeoffs were performed by dispatchers (and pilots) to support goal completion. The premise is that, ideally, the goal of flight planning is to generate a route that is safe, is legal, adheres to company policy, is efficient, and is comfortable for passengers and crew. However, during the task of flight planning, inevitably certain desires will be compromised in order to achieve the higher order needs (namely safety and legality). For example, at times, comfort will be sacrificed to gain efficiency (time and fuel), efficiency and comfort will be sacrificed to ensure adherence to company policy of acceptable hazard thresholds (e.g., NWA has very stringent requirements for "acceptable" levels of turbulence that they will plan flights through), and at times company policy, efficiency, and comfort may be sacrificed in order to adhere to legal requirements (e.g., minimum fuel requirements). There may even be a time when a pilot needs to compromise legality, company policy, efficiency, and comfort in order to maintain safety.

The identification of these trade-offs imply a functional requirement for the system to allow the user to switch between these operation contexts when flight planning. Figure 4.3 below shows the optimization hierarchy of weather hazard avoidance trade-offs that operators perform to support strategic routing decisions.

| |
|---|
| Safety |
| Legality |
| Company Policy |
| Efficiency |
| Comfort |

**Figure 4-3. Optimization Hierarchy**

**Flight Plan Decision Making Stakeholders**

Numerous constraints can affect the routing of a flight, i.e., where you can't go/ where you shouldn't go. Numerous interested parties may want to restrict travel through a particular region. For example, a regulatory agency may prohibit flight over a politically hot region or flight over water because of aircraft type or equipage. An airline policy may restrict flight over a country that may have heavy overflight fees, or may restrict flight through a certain level of predicted turbulence. Although these are not exclusively "weather hazards", they are constraints on the flightplan. Because all of these parties have an interest in the safety of the flight, any one many impose a restriction upon the planned route; hence, they all need the ability to restrict travel or define a no-fly zone.

Figure 4-4 below shows the decision making order of constraints upon a flight plan.

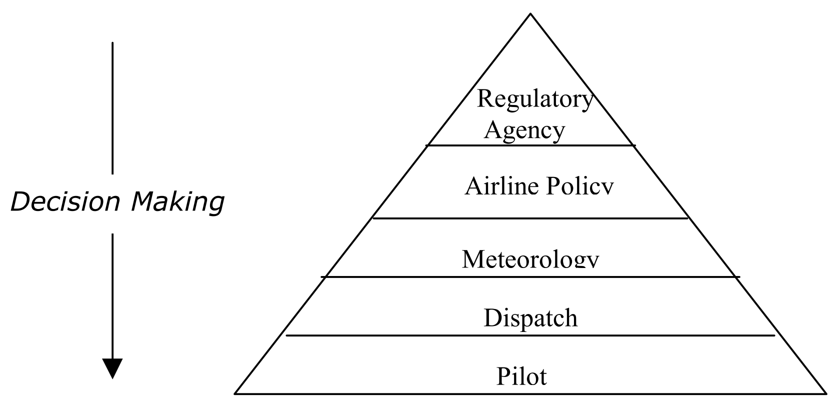


**Figure 4-4. Constraints on Flight Path Determination**

**Hazard Avoidance Maneuvers**

Turbulence, Icing, Volcanic Ash, Convective Weather, and areas of High Ozone Concentration were identified as meso-or macro-scale hazards to the aircraft during cruise flight. Note that micro-scale weather phenomena e.g., low-level windshear, wind gusts, etc., were not included because it was felt that these were hazards for tactical avoidance and our concentration is on the strategic avoidance of hazards. The hazards identified all vary in the manner in which they effect the route planning because of their differences the way they effect the aircraft and strategic route planning priorities. The maneuver around a weather hazard will vary depending on the hazard type, intensity, coverage, and location. Some hazards are more often routed around vertically and some horizontally. Table 4.3 below lists hazard type and most commonly associated avoidance maneuver.

## Table 4-3. Hazard Avoidance Maneuvers

| Hazard Type | Maneuver |
|---|---|
| Turbulence | Vertical |
| Convective | Above or Around |
| Icing | Vertical |
| Volcanic Ash | Lateral |
| Ozone | Below |

**Hazard Levels**

Because of the diverse features associated with each weather hazard, some are more easily predicted than others are, and some hazard predictions have higher resolution than others do. By nature, an unstable airmass of convective activity is more difficult to predict; therefore, it is a more subjective forecast. Because of this, one of our recommendations is that the user should be able to delete indicated weather hazards that he or she expects to not affect the flight and insert potential hazards in order to explore contingencies. For example, if the dispatcher anticipates that convective weather may form in two hours ahead of an aircraft, he or she should be able to insert the weather hazard to assess the potential impacts on the flight plan.

As previously mentioned, a hierarchy exists for flightplan optimization. For example, sometimes the operator may be willing to accept a route through occasional turbulence if it results in appreciable fuel and time savings. Sometimes, it may be just as easy to go around an area of known hazard as to go through it because you have time to waste (e.g., you have a required time of arrival to meet). The decision of whether or not to go through a hazard quite often just depends on numerous factors such as time of day, aircraft type, connecting flight requirements, overall schedule delays, conditions at alternates, etc. The ability of trading-off pros (e.g., getting crew and planes to a destination faster) and cons (e.g., bumpier ride) of going through a hazard imply the requirement for multi-level hazard descriptors.

Hazards are amenable to level descriptors by nature of their effect on the operation. As mentioned previously in the report, quite often weather hazards are described with an associated severity index, e.g., severe icing. The question then is how many levels should be used to describe the hazard. Appendix E of Reference 1 contains a sampling of some current and experimental weather hazard depictions. Some experimental products contain a scaling of 1-100. Is there any usefulness in knowing that the severity index level is a 67 instead of a 66? Doubtful if (a), the user can not discriminate the risk difference between a 67 and 66; and (b), if the user the user will react the same regardless of whether the severity level is a 67 or 66. The determination of the appropriate number of hazard levels was accomplished by plotting hazard type against reasons why a dispatcher or pilot may want to route around or through a hazard (taken form the optimization hierarchy). Table 4 summarizes the results.

**Table 4-4. Hazard Levels**

| WX Hazard | Comfort | Efficiency | Company Policy | Legality | Safety | No. of Levels |
|---|---|---|---|---|---|---|
| Convection | | × | × | | × | 3 |
| Turbulence | × | × | × | | × | 4 |
| Icing | | | × | × | × | 3 |
| Volcanic Ash | | | | | × | 1 |
| High Ozone | × | | × | | × | 3 |

## *4.4 Display Concept*

This section summarizes the factors considered in designing the AWIN display. This concept represents the integration of human factors and human centered design strategies. All color assignments, along with the proposed display layout and display controls are the result of the integration of human factors guidelines and the preceding analysis of user required functionality. This information is used to create a conceptual display which was continually reevaluated and critiqued - components were altered, removed or added, ideas tried and discarded until a final design emerged. This conceptual display represents the designer's best solution to effectively meet required functionality and user needs.

Appendix F of Reference 1 contains two static display concepts, one containing "raw data" with overlaid polygons, and the other only showing polygons of hazardous weather areas. The latter version was implemented for evaluation and a representative screen is appears in Section 5 (refer to Figure 5-2).

**Aviation Conventions**

The display design attempted to utilize currently adopted display conventions with the intent of maintaining uniformity where possible, but was not limited to these conventions where they did not serve the identified functionality.

Previous design strategies have employed the notion of the "dark cockpit", advocating subdued colors for normal operations with the aim of reducing eyestrain and increasing readability across environmental conditions. Additionally, the use of black as the background color upon which the display elements are generated is almost universal in current generation aviation displays. Therefore, this same convention was adopted for the AWIN display.

Numerous color and symbology conventions were also adopted for use in the AWIN display and include: magenta colored "active route" elements, magenta colored "sequenced" waypoints, white colored "next" waypoints, airport, navaid, and present position symbology. The placement of the vertical display beneath the lateral display is also a common convention in avionics displays.

The display utilizes a "north up" convention common throughout aviation and existing meteorological displays. In order to accomplish strategic planning activities, the AWIN tool will be required to accommodate the large geographic areas involved in international travel, as well as the large scale of weather phenomena. Several methods of presentation were considered, but a modified conical projection was used.

While this method is not prevalent within the existing avionics display suites, it is not unfamiliar and it is used within meteorological circles. It was felt that any potential difficulties that may arise from the relative novelty of the method would be offset by reduced distortion inherent in the projection of a three dimensional object upon a flat surface. While not currently used aboard aircraft, pilots are not unfamiliar with this mapping technique. It is used for the depiction of geographic and navigational features in World Aeronautical Charts (WAC) used in flight planning and navigation. These charts are used for strategic planning purposes. Therefore, is seems reasonable to conclude that such a method of depiction fits well with the strategic role intended for the AWIN tool. It should be noted that current flightdeck weather displays are designed to support their use in short term, tactical functions. The AWIN display design for onboard aircraft use may be different than those used by dispatchers, due to the lack of direct cursor control of display elements, the smaller size and lower resolution available from onboard display hardware, as well as the different task focus.

**Meteorological Conventions**

No universal convention for the color coding of weather data has emerged, with each data provider using its own color schemes. Therefore, it was determined that a unique color scheme, one that would best support the intended functionality, would be adopted for use in the AWIN display.

**Color**

The AWIN display was designed for 1024x768 resolution with 8 bit (256) color – a minimum format specification to accommodate the widest range of user equipment. Therefore, the display elements, when used with more capable equipment, should provide even greater levels of distinction between weather phenomena, intensity and coverage.

Each weather hazard is depicted by a single primary color, with intensity of weather coded through gradients of darker (least intense) to lighter (most intense). Since the display was designed with 8-bit color, there were essentially five colors which could be readily differentiated; red, blue, green, yellow, magenta, black, white. Black, magenta and white already assigned as noted. Green was chosen for geographical features and political boundaries due to the high contrast against the black background. Land masses themselves were given a color only slightly lighter than black. The intent was to allow the user to distinguish between landmass, water and political boundary - increasing display readability and situational awareness without distracting from the more important weather information being conveyed. Latitudes and longitudes, along with their respective degree value, were similarly depicted.

Red, with its historical association as a warning, was assigned to the weather phenomenon identified by interview as most important – convective activity. The remaining color assignments were determined in a more arbitrary fashion. Blue – icing; yellow – turbulence; brown – ozone; gray – volcanic ash. Additionally, a distinct "custom" pattern was included to distinguish unique user defined hazard areas, such as active MOAs.

Each hazard color was then assigned a number of color gradients to indicate severity/intensity, with coverage inherent in the graphical display of the phenomenon. For example, convective activity was determined to consist of three distinct levels of intensity while volcanic ash only one. Therefore, three shades of red where used to indicate increasing severity of convective activity. Darkest shades indicate lowest level while lighter shades indicate more severe weather. This convention was dictated by the choice of a dark background environment; lighter shades being most quickly identified. These shades were optimized to provide the maximum differentiation allowed in the 8 bit environment and may not be entirely sufficient.

Since weather phenomena, such as convective activity and turbulence, quite frequently occur in the same vicinity, hazards can cluster on the screen. It was determined that the drawing order of objects should reflect the ranking dispatchers assigned to the different hazards: volcanic activity first, level 3 convection second, followed by level 3 icing, level 4 turbulence and level 2 ozone. While users can filter phenomena to view only those classes of current interest, it was felt that the system should make some provision to present phenomena, where they occur concurrently, in order of importance to the user.

**Functionality**

After the static conceptual display had been created, the challenge became one of integrating the concept with underlying optimization functionality for the evaluation. Many information requirements were deemed out of scope for the evaluation but a high priority subset was developed to guide prototyping. These requirements addressed content, format, interaction, and system functionality.

Content
- hazard type (i.e., turbulence, icing, volcanic ash, ozone, thunderstorms, or other)
- hazard location vertical
- hazard location horizontal
- hazard severity (1 through 4)
- hazard movement history
- hazard movement prediction
- hazard coverage or density
- winds aloft forecast
- planned route
- flight performance data of planned and actual routes

Format
- hazards by type and risk
- route of shortest distance
- route of efficiency
- route of "comfort" around level 1,2,3,and 4 hazards
- route of "efficiency" around level 2,3, and 4 hazards
- route of "company standards" around level 3 and 4 hazards
- route of "safety/legality" around level 4 hazards
- route of "custom" around acceptable hazard levels by hazard type (e.g.,
- status of flight
- temporal relations between flight path and hazards
- user entered hazards
- automatic generated hazards

Interaction
- user input of multi-level 4-D polygon hazards
- ability for user to modify routes through direct manipulation
- ability for user to change route shown by customizing acceptable level of hazard avoidance by hazard type (e.g., I will go through level 3 and lower hazards for icing, but only level 2 and lower for turbulence)
- ability for user to compare several routes for fuel and time

System
- automatic generation of multi-level 4-D polygon weather constraints for tubulence, icing, volcanic ash, and high concentration of ozone areas
- automatic generation of great circle paths
- automatic generation of wind-preferred routes
- autmatic generation of routes optimized around unacceptable hazard of weather

Thus, the evaluation task would evaluate not only our requirements, but also the implementation. The next section describes the features of the User Interface and Route Optimizer that were implemented for laboratory evaluation. Additional explanation of the AWIN tool and functionality are contained in Appendix C, "Briefing Guide"

# 5.0 Description of AWIN Decision Aid

This section provides a summary of the functions, software structure, and weather data interfaces of the AWIN decision Aid that were implemented for evaluation by pilots and dispatchers. In the following discussion, the decision aid developed under this study will be referred to as "AIRWAy" (Aiding Interface for Routing and Weather Avoidance).

## *5.1 Major Functions*

The AIRWAy tool, shown in Figure 5-1, contains a Graphical User Interface (GUI) and a Route Optimizer. This latter function uses wind and weather data as well as other information needed for route optimization.

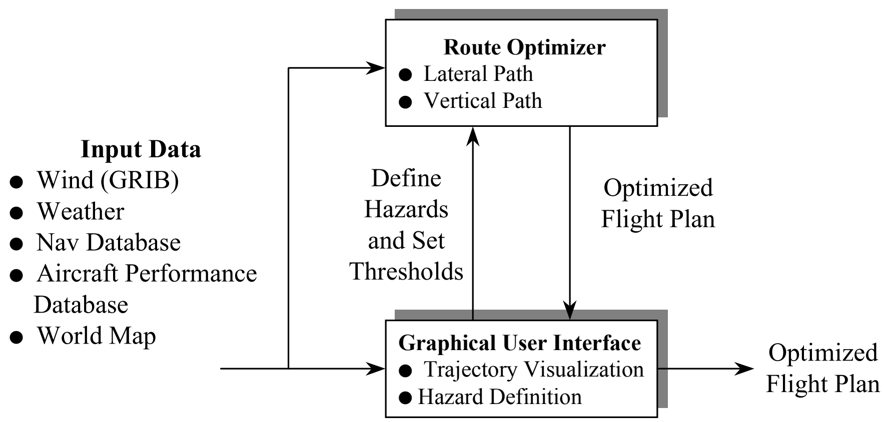


**Figure 5-1 Functional Diagram of Honeywell's AWIN Decision Aid: "AIRWAy"**

The design of the AWIN GUI was described in Section 4.0. Based on these UI requirements, the display provides three views: the "world view", the "profile view", and the "control panel" view as shown in Figure 5-2.

The world view shows a globe with land masses and various weather hazards and trajectory options superimposed on it. The profile view shows the vertical profile of a selected aircraft route, as well as the vertical profile of any relevant hazards. The control panel view is a collection of controls and alphanumeric displays which convey additional information about the selected route and the current hazard set, as well as controls to manipulate the hazards, routes and flights.

In addition to the three views, there are two major dialog boxes that are invoked when the user wishes to create or edit a flight or route, or to create or edit a hazard. By filling in the fields of these dialogs, the user is able to provide the route planner with all the data required for calculating a route.

The route optimizer supports user decisions by computing optimum flight plans with several user selected options:

- Standard cost function with the usual fuel versus time trades
- Addition of wind data and computation of a "wind optimal" route

- Addition of weather hazards to automatically route around (laterally and/or vertically) all hazards whose severity meets or exceeds the "no fly" threshold.

As shown in Figure 5-2, the control panel considers five weather hazard types (convection, icing, high ozone concentration, turbulence and volcanic ash) plus one custom (user defined) hazard. The rationale for this design is contained in our Phase 1 report [ref. 1].

The slider switches set individual thresholds for each of these hazards. Hazards whose severity exceeds the threshold become "no fly" zones for the route optimizer.

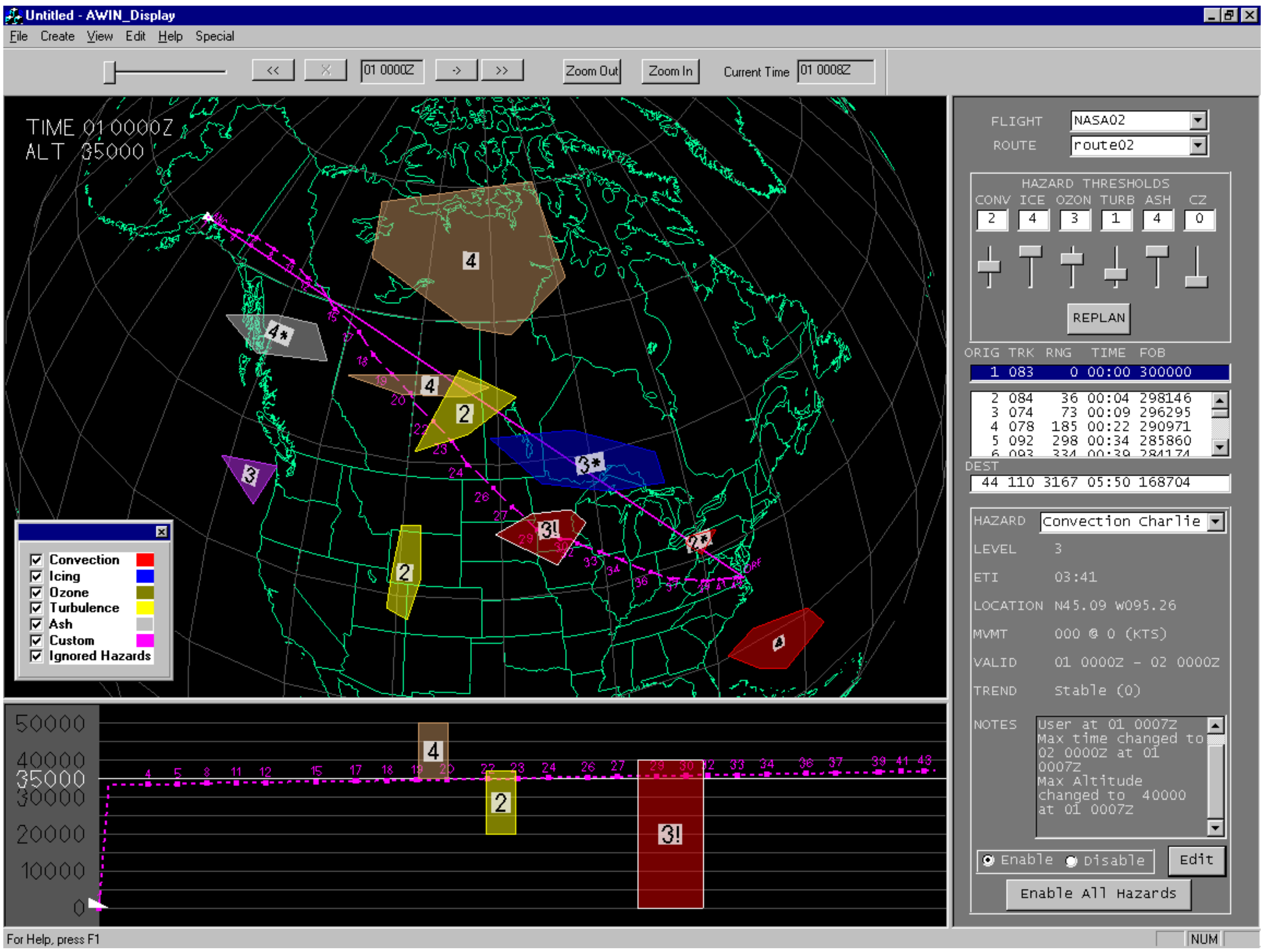


**Figure 5-2 GUI Developed for AIRWAy**

### 5.2 Software Structure

A top level description of the AIRWAy software tool is shown in Figure 5-3.

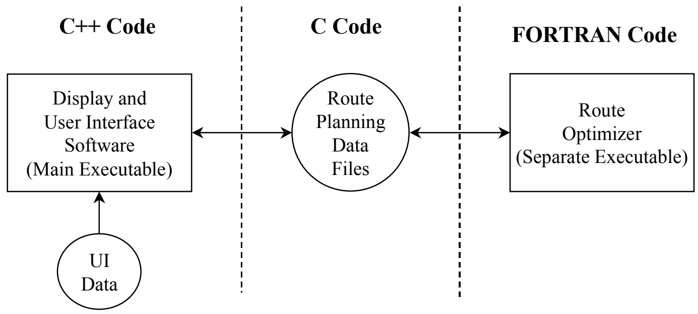


**Figure 5-3 AIRWAy Software Structure**

The  Display and User Interface software is a Win32 application written in C++ that handles the interactions between the user and the route planning software.  The display was written using components from the Microsoft Foundation Class (MFC) library.  MFC is a collection of templates which allow the swift construction of standard Windows interface components such as buttons, drop-down list boxes, menus, etc. The resulting software is thus constructed in a standardized fashion, which simplifies maintenance and expansion.  The display is concerned solely with user interaction; all of the route planning and related data management is handled by a partner application.  The display software shares a variety of data files with the route planning software, such as the hazard definitions.  It also uses some files not used by the route planner, such as the list of airports.

The Route Optimizer is a stand alone executable written in Fortran.  The design of this function was described in Section 3.0 and is a derivative of previous trajectory optimization software developed at Honeywell.

Communication with the route planning software is done through a well-defined interface of access functions and data files written in C.

The process view of AIRWAy is shown in Figure 5-4 which illustrated the relationship of the two executable modules.

As described in Section 6, this tool was evaluated with a set of pilots and dispatchers.  Several features were addded to the GUI and Display software to support testing.  The display software also records the activity of a test subject, to aid in the analysis of the UI design.  The display implemented this feature by writing out a text file with a time stamp for each basic user action, such as clicking on a button or selecting a hazard.  In combination with the other experimental recording techniques, this provides a complete picture of what actions a test subject takes while working through a scenario.

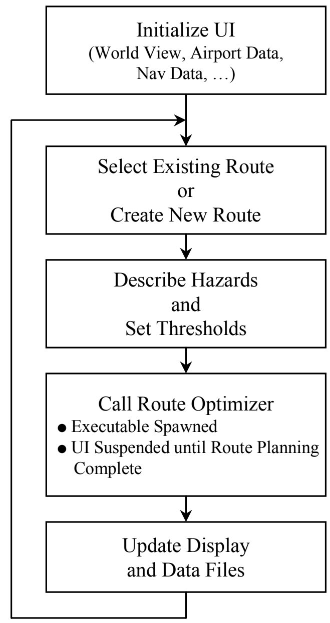


**Figure 5-4 AIRWAy Process View**

### *5.3 Interface to Weather Data*

Table 5-1 contains a list of the parameters used by the AWIN route optimizer to define weather hazards for use in the Route Optimizer. These parameters define each individual polygon hazard and can be manually entered using the AWIN GUI.

**Table 5-1 Polygon Data Structure**

| Parameter | Description | Example |
|---|---|---|
| Label | Hazard name, consisting of type name and sequence designator (alpha, bravo, ...). This is used for information purposes only, since it is uniquely determined in the UI by TYPE (below) and other of definition. | “Ozone Charlie” |
| Type | Hazard Type Enumerator<br>1 = Convection<br>2 = Icing<br>3 = Ozone<br>4 = Turbulence<br>5 = Vocanic ash<br>6 = User Defined | “Type 3” |
| Level | Hazard severity [1 (least) through 4 (most)] | “Level 4” |
| Cost Factor | Hazard cost factor. In the current UI model, this will always be zero (ignore) or "large" (avoid) | “COST_FACTOR 100000” |

| | | |
|---|---|---|
| | (output from UI to route planner) | |
| T_ISSUE | Time that hazard was defined.<br><br>Time is **entered** and **displayed** in the GUI as "MM DD hhmmZ".<br><br>MM = Month, DD = Day, hh = Hour,<br>mm = Minute (Z for Zulu or Universal Time).<br><br>Time is internally **represented** as the number of minutes since 01 01 0000Z. | "T_ISSUED 20" |
| T_INITIAL | Time that hazard location is defined which becomes the reference for hazard motion. | "T_INITIAL 100" |
| T_MIN<br>T_MAX | Hazard is valid only in the time range form T_MIN to T_MAX. | "T_MIN 0"<br>"T_MAX 500" |
| ALT_MIN<br>ALT_MAX | Hazard is valid only in the altitude range from ALT_MIN to ALT_MAX. | "ALT_MIN 29000"<br>"ALT_MAX 45000" |
| Speed | Speed of hazard in knots | "SPEED 50" |
| Heading | Initial heading of hazard, defining great circle track (degrees counterclockwise from North). | "HEADING 80" |
| Trend | Size trend of hazard (used for information purposes only)<br>-1 = Decreasing<br>0 = Stable<br>+1 = Increasing | "TREND 0" |
| NPOINTS | Number of points defining hazard polygon | "NPOINTS 6" |
| LATLON<br>.<br>.<br>. | Latitude and longitude of each vertex in degrees N and E (negative for S and W), respectively from 1 through NPOINTS. | "LATLON 43 -76"<br>"LATLON 39 -73"<br>"LATLON 43 -68"<br>"LATLON 47 -69"<br>"LATLON 49 -73"<br>"LATLON 46 -76" |
| BEGIN_NOTES<br>END_NOTES | Tokens denoting start and end of note field. Any text can be put in the note field by the operator. In addition, the software will make automatic time stamps any time a change is made, identifying the nature of the change | "Sample data file" |

## 5.4 Software Implementation

The current AWIN Decision Aid is composed of software modules in C, C++, and Fortran and is compiled to run on a Pentium based PC. There are no limitations in the software regarding the number of number of weather hazards that may be considered or the number of vertices that a polygon may have. The current naming convention (Alpha, Bravo, etc. ) limits the prototype implementation to 26 hazards. Of course, the problem complexity does drive the memory and processing requirements needed to run the AWIN tool.

As an example, a sample file of seven hazards with the number of vertices per hazard ranging from N=3 to N=6 consumes about 2.2 Kbytes of memory. Running the route optimizer with this file takes 5 – 10 seconds on a 200 MHz class PC. Roughly ten percent of the processing time is spent checking polygons hazards. The time spent checking polygons grows approximately linearly with the number of polygon edges. Thus, there is a throughput penalty associated with using polygons with a large number of vertices.

The next section describes the laboratory evaluation of the AWIN decision aid.

# 6.0 Evaluation of AWIN Decision Aid

This study was an initial assessment of the utility and usability of the AWIN concept for weather-related route planning. This is the first in an anticipated series of AWIN evaluations. Ultimately, we would like to directly compare the ability of users to perform weather-related flight planning tasks and maintain weather-related situation awareness with and without AWIN. However, a variety of limitations dictated that this first study be a "stand alone" usability evaluation of the AWIN concept. There were seven main objectives of this study:

- Assess the usability of the functions and interface features of the AWIN concept
- Assess the ease of information access using AWIN
- Assess how AWIN might be used instead of or in addition to current flight planning tools
- Determine if there are differences in usability or acceptance from different user perspectives (i.e., dispatchers, airline pilots, bizjet pilots)
- Evaluate the effect of differences in information reliability on use of AWIN
- Assess the ability of the AWIN concept to support situation awareness
- Assess the ability of the AWIN concept to support decision making

## *6.1 Method*

The study used both analytic and observational evaluation methods for concept evaluation (Ref. 2).

**Analysis methods**

A combination of features of "expert walkthrough," "keystroke-level model analysis," "questionnaire," and "structured interview" techniques were used in the process of collecting usability feedback on the functions and features of the AWIN prototype.

Pilot and dispatcher experts "walked through" scripted activities (organized into scenarios) using the AWIN prototype. Several types of recorded data were collected as, and after, subjects performed these activities. The scripts involved performing five types of tasks common to all scenarios: (1) creating Great Circle, wind preferred, and wind preferred/weather constrained routes; (2) creating weather hazards; (3) setting/resetting hazard thresholds; (4) replanning routes after introduction of new or modified weather hazards; and (5) replanning routes by adding/removing waypoints. Each scenario involved a different flight plan and different weather conditions, and the details of the execution of each type of task was different. Structured interview questions and written questionnaire questions were used to solicit expert opinions and comments on the usability and utility of the prototype. Interview questions were posed as subjects were using the prototype. Questionnaire questions were presented after completion of the scenarios. Interview questions were crafted to assess the ease and speed with which users could access requested information (see Appendix XX for the scenario descriptions and the real-time interview questions). The written questionnaire included both a series of specific "closed" questions (i.e., the answers are constrained), and open-ended questions (i.e., questions that allow free comments to a specific question rather than choosing from a list of responses) directly soliciting user opinions on the usability and utility of AWIN features and functions (see Appendix XX for the post-test questionnaire).

A very informal keystroke-level model analysis of the "walkthrough" scenarios was used to augment the interview and questionnaire data. That is, one of the design team members who was highly familiar with the AWIN concept performed the same set of scripted activities that the subjects did, and her action sequence and times to perform the activities were used as a benchmark of nominal task performance against which to compare subjects' task performance in terms of the sequence of button pushes and response times.

**Observational methods**

"Direct observation" and "experiment" methods were also used to evaluate the AWIN concept. In terms of direct observation, as the user performed the scripted activities described above, the experimenter directly observed the user and recorded problems that occurred with the user/system interaction. The experimenter took notes in real time reflecting important issues and comments that surfaced as the user walked through the scripted scenarios. In addition, the prototype had a "help" button with the experimenter acting as the "help" function in a "wizard of oz" fashion. The experimenter helped the user solve the problem and recorded the event in her notes. The whole session was videotaped.

The analytic and observational methods described above focused on scenarios where subjects performed tasks that were scripted, activity by activity. The only manipulated variable for these scripted activities was "subject type," that is, three different types of users, airline pilots, corporate pilots, and airline dispatchers, participated. The controlled experimental aspect of this study involved variable manipulations and data collection revolving around subject use of the AWIN prototype on two "goal-driven" scenarios. In these scenarios, subjects were instructed only with an operational objective, where the instruction included a manipulation of information reliability. Scenario A was a "low information reliability" (LIR) condition where subjects were instructed:

> "*Plan a flight from Minneapolis (MSP) to Hong Kong (HKG) that is scheduled to leave at 0240Z. Imagine that this aircraft is a B747. Fuel prices are exorbitant and the company has been emphasizing the desire to save costs where practicable. ATC has given you a mandatory fly-over waypoint of Anchorage. In making your final flight planning decisions, assume that turbulence and convection hazards over the pacific are all associated with a very unstable weather system so the accuracy of the location and severity prediction is moderate (60% probability of occurrence as depicted)*."

Scenario B was a "high information reliability" (HIR) condition where subjects were instructed:

"Plan a flight from Minneapolis (MSP) to Miami (MIA) that is planned to leave now at 0300Z (flight has been delayed 2 hours). Imagine that this aircraft is a DC-9 (note: performance calculations will be inaccurate, but please play along) and the majority of passengers are booked on a NW vacation that is connecting with a cruise ship so it is high priority that this airplane get to Miami as soon as possible. Also, ATC is currently routing all traffic around Georgia because there has been a state-wide power failure and they are in a state of chaos. In making your final flight planning decisions, assume all hazard locations and severity levels are highly stable, such that meteorologists would give a 98% probability to the likelihood of occurrence as depicted."

The design of the experimental aspect of the study was a 3X2 mixed design, with subject group (airline pilots, corporate pilots, and airline dispatchers) as a between-subject variable, and information reliability (LIR, HIR) as a within-subject variable. Figure 6-1 shows the experimental design. The subjects were run on these experimental scenarios after they performed the scripted scenarios, and Scenario A, the low information reliability scenario, was always presented first.

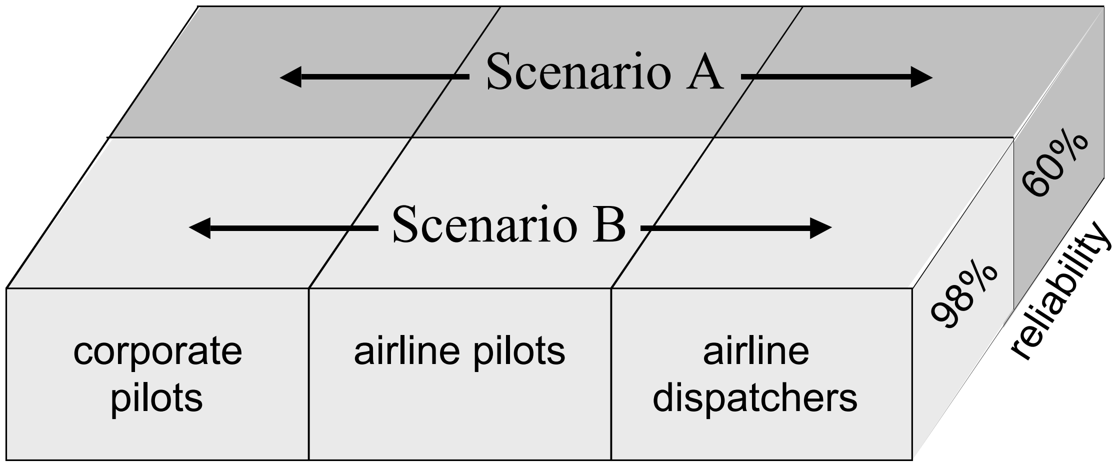


**Figure 6-1 Design for controlled experiment aspect of study.**

In addition to the button push and response time measures described above under "key-stroke level model analysis," measures were also collected under this portion of the study to assess decision making quality and situation awareness (SA). To assess decision making, total fuel, total time, and "inappropriate hazard intrusions," (routing through hazards with hazard levels higher than hazard threshold settings) were recorded for the selected route.

For SA assessment, a set of SA questions was composed that covered the three SA levels described by Endsley (1995), that is, the component level, the integration level, and the prediction level. Endsley's "freeze" technique was used where the screen is unexpectedly blanked and the subject is asked a series of questions which he or she must answer without the advantage of accessing information from the display. The "freeze" point was specified to be at a comparable point in both scenarios, immediately after the subject had made his or her final routing decision. The SA questions used were:

**SA Level 1 -- Component**

_ Is the active route a great circle route, wind preferred route, or wind and hazard preferred route?
_ What altitude is being displayed on the lateral display?
_ Is the time slice displayed earlier than, the same, or later than, the real time?
_ Draw the location, type, hazard level, and hazard code (if any) of as many hazards as you can on the map attached.

**SA Level 2 -- Integrated**

_ Is your current active route planned through any hazards?
_ If yes, why. If not, why not.
_ How much time and fuel penalty is there for the wx/wind preferred route over the wind preferred route?

**SA Level 3 -- Prediction**

_ Which routes result in flying through hazards?
_ Do any routes result in flying through hazards higher than the hazard threshold?
_ What type of hazard will be encountered first (if any) for the active route?
_ Do any of the routes unnecessarily plan around hazards? Which ones?

**Subjects**

Twelve subjects volunteered to participate in this study, and were provided with a small remuneration for their time. While the initial aim of AWIN is use as a dispatcher tool, we believe there is potential for use in the cockpit as well. To gather feedback from the cross-section of potential users, four airline pilots, four corporate pilots, and four dispatchers were recruited, all based in the Minneapolis, MN area. A demographic summary of the subjects is given in Table 6-1.

## Table 6-1 Subject demographics.

| Variable Group | Age (Mean) | Age (Range) | Avg Experience | Gender (M/F) | Avg Years Education |
|---|---|---|---|---|---|
| **Dispatchers** | 44.5 | 35-57 | 16.5 yrs | 3/1 | 14.75 |
| **Corporate Pilots** | 41.0 | 29-53 | 6550 hours | 4/0 | 16 |
| **Airline Pilots** | 37.25 | 30-45 | 9525 hours | 3/1 | 16 |
| **Total** | 40.92 | 27-57 | ---- | 10/2 | 15.6 |

**Apparatus and Materials**

The apparatus was a computer workstation comprised of a 21" Viewsonic brand monitor (Model P815) operating at 85 Hertz, 32 bit color and a resolution of 1152 by 864 pixels per inch. The computer was a Dell Precision 410, dual 400Mhz Intel processors, 7.5 Gig hard drive and 260 MB RAM. It was also equipped with a Dell QuietKey extended keyboard and Microsoft Mouse (two key). The computer operating system was Microsoft Windows NT(tm) Workstation, version 4.0. AWIN was implemented in Visual C++ and Fortran. When weather hazards were created, they appeared instantly. When routes were calculated, they took 5-10 seconds to calculate.

Materials consisted of those provide to the subject before the test (consent form, demographic questionnaire, briefing guide), during the test (the blank map on which subjects drew hazard locations, levels, codes, etc.), and after the test (post-test questionnaire). In addition, the experimenter used, but did not show the subject: (1) a scenario/question sheet to script the scenarios and the interview questions; (2) a written instruction sheet describing the objectives of the "goal driven" scenarios; (3) separate question and answer sheets for the situation awareness questions; and (4) a log to record notes, "help" requests, and the answers to the situation awareness questions. These materials are included in Appendices A through E.

**Procedure**

Subjects were scheduled for four hour sessions, and either one or two subjects were run a day. Each subject was first seated in a briefing room, and began the study by filling out the consent form and the background questionnaire. Then the general purpose of the study was described, and the subject was given the briefing guide to read, which described the purpose of the AWIN concept, and the functions and features that would be used in the study. The briefing guide is included in Appendix C. This briefing portion of the study took approximately 30-45 minutes.

Next, the subject was brought to the test room where the AWIN concept was implemented on the workstation. The subject was seated in front of the workstation with the experimenter to the side, and a "hands on" briefing of how the concept worked was given. Every feature that the subject would exercise was reviewed, both in terms of the intent of the feature and how to use it. This was followed by having each subject perform two practice scenarios, which required the subject to exercise all the features of AWIN that would be used in the test scenarios. This familiarization/training portion of the study took approximately 30-45 minutes.


**Figure 6-2 AWIN evaluation workstation**

The test itself consisted of performance of the 10 scripted scenarios and 2 “goal-driven” scenarios. The scenarios were always run in the same order. The scenarios took approximately 5-10 minutes each. Subjects began each scenario by using the “Special” function on the upper menu bar to reach a “Macro” function which allowed them to login to start data recording. The Macro function was also accessed to conclude each scenario and to stop data recording. They then performed the commands and answered the questions for each scripted scenario. Finally, they were given the instructions for the two “goal directed” scenarios. In these scenarios, when they made their final routing decision and executed the final route, the screen was blanked and subjects were asked the SA questions. The experimenter recorded the answers to the SA questions with the exception of the question that required subjects to draw hazards on a blank map. The test portion of the study took approximately 1 1/2 - 2 hours.

After completion of the prototype testing, subjects were brought back into the briefing room and filled out the post-test questionnaire. The subject was then asked to describe how the types of tasks that had been performed here were performed with his or her existing equipment. Finally, the subject was asked for wrap-up comments and thoughts. The post-test session normally took between 30 and 45 minutes.

## *6.2 Results*

There were three different types of potential users of the AWIN tool represented in the evaluation:

- international airline dispatchers,
- airline pilots, and
- corporate pilots.

Hence, data will be compared by subject type. The results will be broken into three categories: scenario objective data , information reliability manipulation data from the freeform scenarios, and additional subjective data from the pre- and post-experimental questionnaires.

**Scenario Objective Data**

A macro program was created that recorded user inputs into a data file. This data file contains the subject and trial number; a recording of the button variable name of the object clicked, e.g., FLIGHT_P_CHECK_WEATHER; the action, e.g., Turned off; and the time in seconds into the trial that the even took place. Objective data reported includes scenario completion times, click event counts, interview question accuracy for the scripted scenarios, and help query count.

*Scenario Completion Times*

One method of looking at differences across subject type was to look at completion time for the scenarios. Start time was calculated by when the subject clicked the OK button after completing the "Start Macro" dialog box. End time was calculated by the last click time. Descriptive statistics revealed the mean scenario completion time (averaging all 12 scenarios) for dispatchers to be 390 seconds (sec), airline pilots 354 sec, and corporate pilots 324 sec. An expert user completed the scenarios and it was determined that absolute minimum mean scenario completion time to be 129 sec. The minimum mean scenario completion time was for reference only and not included in any of the analysis. An ANOVA (Analysis of Variance) revealed a significant difference only between the dispatcher and corporate pilot group, $p<.02$. Figure 6-3 shows the mean scenario completion times.

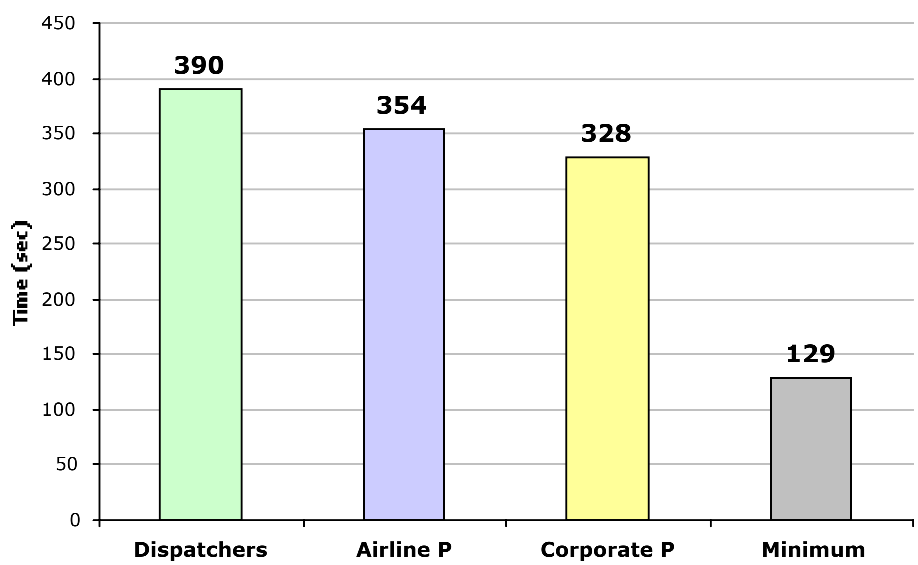


**Figure 6-3 Mean scenario completion time**

*Scenario Click Count*

A count of the number of clicks or user-initiated events was calculated for each subject. A click was counted each time the user selected an item with the mouse or made a keyboard entry. Descriptive statistics revealed the mean click count (again, averaged across 12 scenarios) for dispatchers to be 90, airline pilots 67, and corporate pilots 63. An expert user completed the scenarios and it was determined that absolute minimum mean click count to be 52. An ANOVA revealed a significant difference between the dispatcher and airline pilot group, p<.01, and the dispatcher and corporate pilot group, p<.01. There was not a significant difference between the airline and corporate pilot group. Figure 6-4 shows the mean scenario click counts.

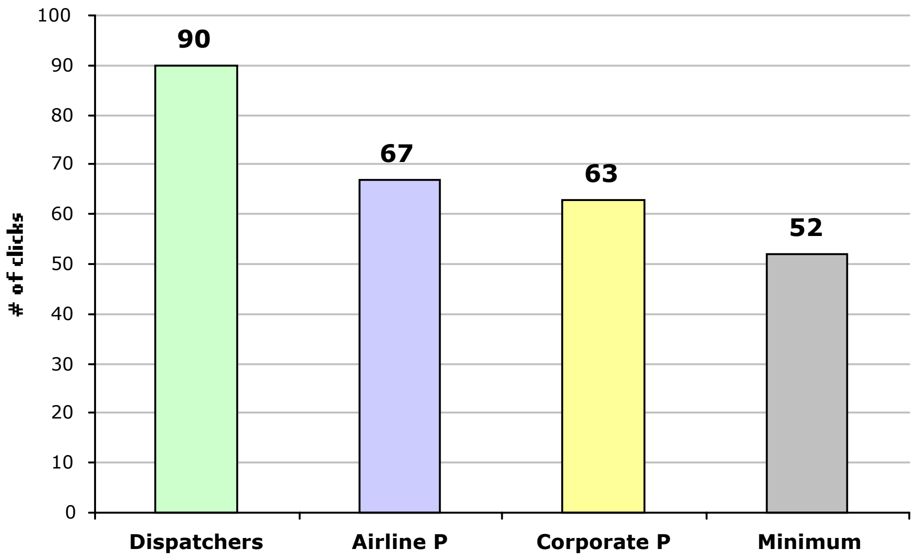


**Figure 6-4 Mean scenario click counts.**

*Interview Question Accuracy*

Throughout the scripted scenarios, subjects were asked questions about the routes they were creating with the AWIN tool. Please refer to Appendix X. for a list of the questions asked. Responses were recorded by the interviewer and later scored for accuracy. The percent correct responses to 37 questions were evaluated for each of the 12 subjects. Descriptive statistics revealed the mean percent of correct responses for dispatchers to be 87, airline pilots 96, corporate pilots 95, and an overall mean of 93. An ANOVA revealed a difference between the dispatcher and airline pilot group, p<.08. There was not a significant difference between the corporate and dispatcher group nor the airline and corporate pilot group. Figure 6-5 shows the mean interview question accuracy scores.

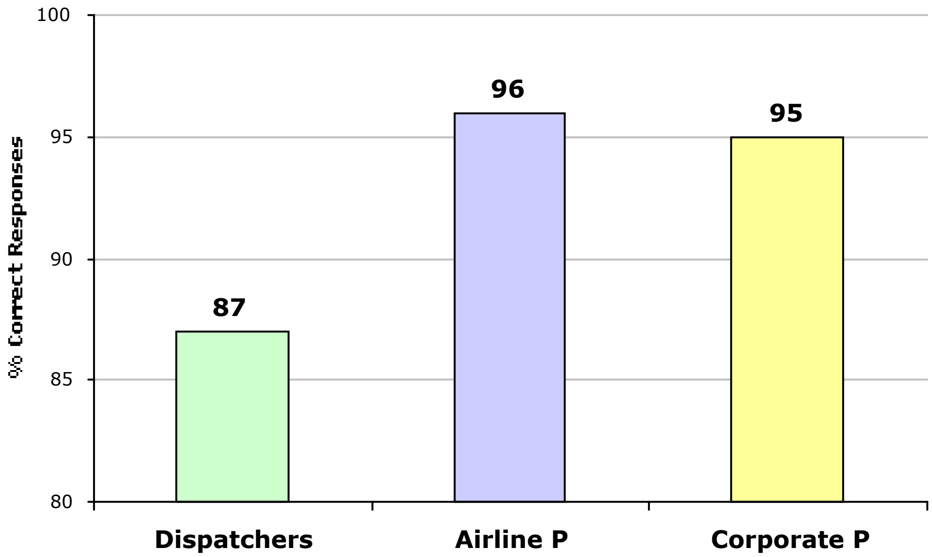


**Figure 6-5 Mean interview question accuracy scores**

The top five most frequently missed questions, accounting for 56% of incorrect responses, are listed below in Table 6-2.

**Table 6-2 Top Five Most Frequently Missed Questions**

| Question | Dispatcher | Airline Pilot | Corp Pilot | Total Misses |
|---|---|---|---|---|
| Will the aircraft flying the wind preferred route fly through any hazards? List. | 2 | 2 | 1 | 5 |
| How long does it take the aircraft (ETE) to complete the last created Wind/Wx route? | 3 | | 1 | 4 |
| What would you do now? (correct answer was nothing because hazard below flightplan) | 1 | | 3 | 4 |
| Which route is the most fuel efficient? | 1 | | 2 | 3 |
| Will the aircraft flying the wind preferred route fly through any hazards? List. | 2 | 1 | | 3 |

*Help Query Count*

A help menu item was available for subjects and they were instructed to access this function anytime they wanted clarification on system functionality. The subject would then direct the question to the experimenter for answering. The total “help request” count across all 12 trials for 12 subjects was 40. This is an average of less than 0.28 questions asked per trial. Dispatchers accessed the help function most with a total of 17 questions. Figure 6-6 provides the total “help request” count per subject group.

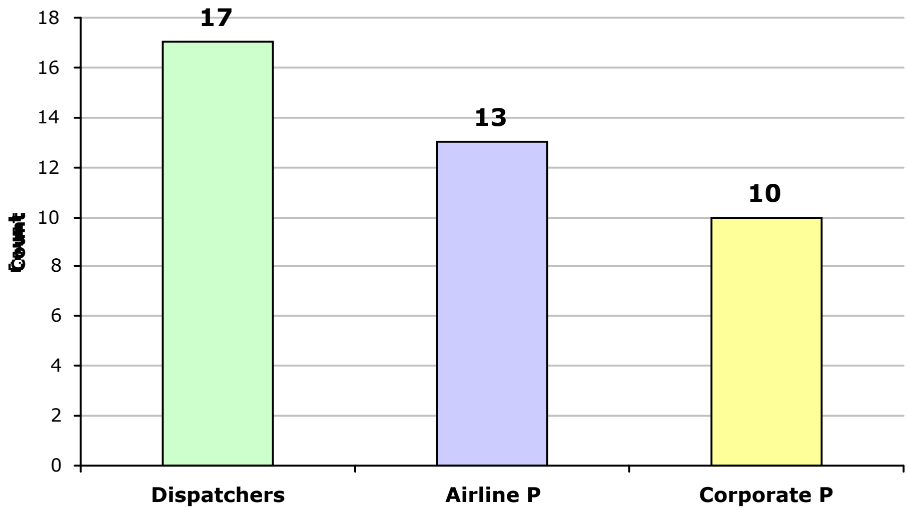


**Figure 6-6 Total help query count per subject group**

**Information Reliability Manipulation Data**

Data particular to the two goal-driven non-scripted scenarios that were collected include scenario completion times, click event counts, situation awareness scores, and subjective questions. Because there were only two trials manipulating information reliability, no inferential statistical tests were performed. Descriptive statistics for completion times, click event counts, and the situation awareness probe are presented as well as a summary of responses to the information reliability question asked in the post-experiment questionnaire.

*Scenario Completion Times*

Mean scenario completion times were calculated for the low and high reliability goal-driven scenarios. The overall mean was greater in the high reliability scenario by 29 seconds. Figure 6-7 shows the mean scenario completion times by subject and condition type.

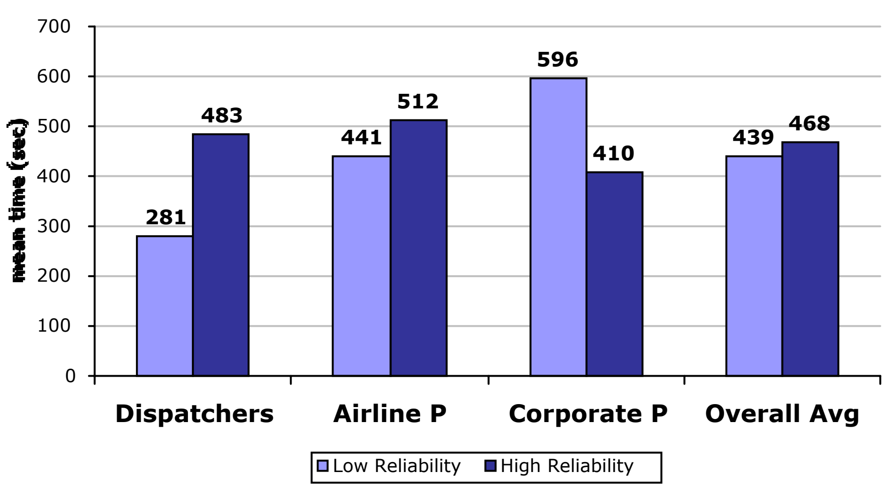


**Figure 6-7 Mean scenario completion times by subject and condition**

*Scenario Click Count*

Mean scenario click counts were calculated for the low and high reliability goal-driven scenarios. The overall mean was less in the high reliability scenario by 28 clicks. Figure 6-8 shows the mean scenario click count by subject and condition type.

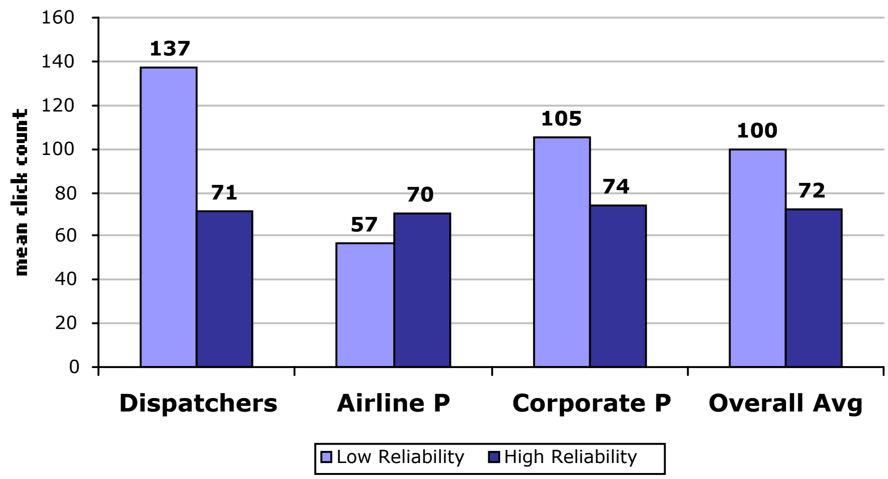


**Figure 6-8 Mean scenario click count by subject and condition**

*Situation Awareness Scores*

A set of situation awareness questions was asked of the participants in both the low and high reliability scenario manipulation conditions. The scoring method employed gave no credit given to wrong answers, half credit given to partially correct answers, and full credit given to correct answers. The mean situation awareness score increased for all three subject groups in the high probability scenario. Thirty-three percent more SA questions were answered correctly, on average, for the high reliability condition than the low reliability condition. Figure 6-9 shows the mean SA scores by subject and probability condition.

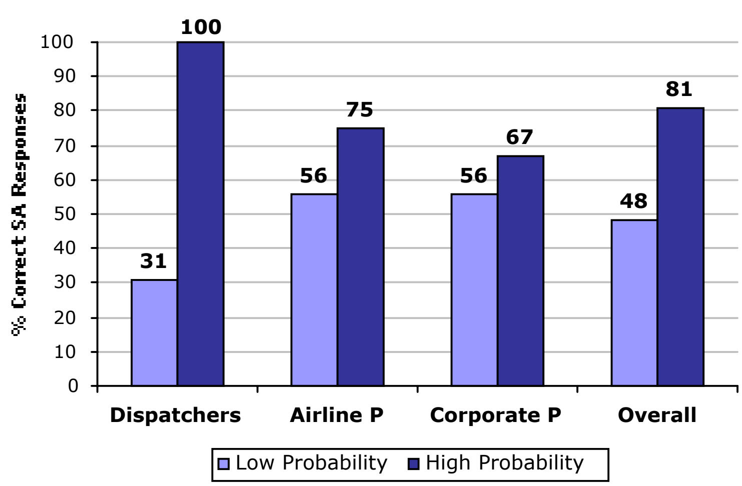


**Figure 6-9 Mean SA scores by subject and condition**

*Subjective Reliability Questions*

At the conclusion of the experiment, subjects were asked to fill out a thirty question questionnaire that can be found in Appendix E. Three of the questions related to information reliability/ probability. A summary of the responses to all three questions is provided below. Responses from dispatchers are prefixed by a **D**, responses from airline pilots by an **A**, and responses from corporate pilots by a **C**.

*How does the reliability of weather information affect your willingness to plan a route through a hazard ?*

**D:** Information from unreliable sources is generally dismissed if other sources can be used. Otherwise, unreliable sources must be used for hazards because of legal constraints.
**D:** If information is accurate, I will avoid wx hazards -- If unreliable, likely to avoid it by wider margin (affecting time/ fuel burn) -- If reliable, able to plan with confidence more closely to best burn rate.
**A:** The better the information, the better decision can be made.
**A:** The more sure I am of the forecast weather, the more weight I give it in planning.
**A**: Timely updates of hazards with reliable information would increase my willingness to fly through a hazard. Too often reports are vague or old.
**C:** It has strong effect. For my flight planning, I am the one who interprets wether trends through my experience. If I don't feel safe flying through a hazard, I won't fly through it regardless of who tells me to.
**C:** If proven reliable, I would use it. It also depends on type of weather.

*Do you generally have less faith in weather hazard predictions further into the future ?*

**D:** Generally, wx forecasts greater than8 hours for hazardous weather tend to diminish the accuracy. I generally look for supporting data to forecast before restricting flight plan route or altitude.
**D:** Looking at it closely and decisions made closer to departure with weather, pilot reports, charts, etc.
**D:** Yes. Conservative.
**D:** Yes I do -- I often see forecasts for wx hazards, 8-10 hrs from present time being mildly inaccurate (and with int'l flights of 10+ hrs in aviation, this is a really big factor). If it is forecast, no matter how inaccurate it may end up being, I have to plan to avoid area or particular altitudes, etc -- which may result in far less than optimal planning/ tradeoff with payload, etc.
**A:** Yes. It depends on the nature of the hazard and it predictability. I decide If I think it will really affect the flight or not.
**A:** Yes, plan around items with lower reliability level.
**A:** No. as equipment is being installed and used properly the accuracy and timeliness of weather info is getting better.
**C:** Beyond 6-12 hours, my faith in hazard prediction diminishes rapidly. Beyond that time frame, I take a wait and see attitude.
**C:** Yes, try to get last minute updates
**C:** Yes less. Still plan avoidance, but develop more options.
**C:** Yes. The need for enroute updating.

*Are there differences in the reliabilty of predictions of certain types of weather events? Explain.*

**D:** The presence of surface or upper fronts help support convective forecasts.
**D:** Time of day and amount of daylight when using pilot reports based on visual sighting of convective or volcanic activity.
**D:** Reduced visability below 1/2 mile have a very low reliabiltiy more than 4 hours and less than 1 mile more than 8 hours. This is generally associated with fss.
**D:** --Upper winds -- Sometimes they are horrendously off -- Seemingly for days at a time -- In more remote areas in particular -- Northern Canada/ Russia for example. -- Convective development -- How line of t-stms are likely to develop over next few hours.
**A:** Yes, convective activity and windshear.

**A:** Yes. Wx associated with a front is easier to predict than general weather effects.
**A:** Yes, frontal weather relative to air mass.
**C:** Prediciton of convective activity has become very reliable where as predictions of lowifr and particularly the beginning and end of low ifr conditions are rather unreliable and often time incorrect by more than 2 hours before or after the prediction.
**C:** Factors that effect the reliability -time of day - how long the system or type has been active - area geopgraphic location
**C:** Thunder-storms and turbulence seem the least predictable
**C:** Yes. Geographically. I routinely operate at remote airports on world-wide scale. Obtaining weather data can be difficult and sometimes locally impossible.

**Additional Subjective Data**

Subjects completed a pre- and post-test questionnaire that provided additional insights into dispatcher and pilot experiences and attitudes towards hazards weather and its effect on flightplanning. Appendices B and E contain the questionnaires used. A summary of some key questions is provided below. Responses from dispatchers are prefixed by a **D**, responses from airline pilots by an **A**, and responses from corporate pilots by a **C**.

*Please explain any particularly difficult experiences working around weather.*

**D:** International weather forecasts are frequently inaccurate beyond 8-10 hours. Most long range int'l flts are dispatched 15-18 hrs in advance so the pilots don't have current weather.
**D:** Wx changes require reroute flight.
**D:** Convective activity -- atc conflict, avoiding typooons and hurricanes, avoiding volcanic ash, avoiding icing conditions.
**D:** Communicating data effectively to crews -- especially when out of acars range and having to resort to arinc/hf radio -- and especially away from range of us radio facilities. E.g., Russia far east or enroute to India. Once crews able to get data and perhaps require reroute, often very difficult to get permission for that reroute -- especially in sensitive areas of the world, Russia, etc. and where ATC facilities are very bad. Within US, problem with ATC overreacting to weather and forcing flight to reroute when we can clearly see via asd/ wx radar that reroutes are overreaction. Company pushes a/c often to the very edge of performance limits -- sending range limited flight onto routes where they are right at max cap on VFR days -- add wx to the equation and reroutes and often flight have to land short of destination for fuel. This is both domestic and int'l. So basically main problems are ATC and airline itself.
**A:** Timely wx updates enroute, long range radar update at destination airport.
**A:** Landing in bad wx with rain and high winds always a challenge.
**A:** Over water convective activity in the north and mid-pacific. Getting timely weather updates.
**A**: Alt and perf limit of a/c in regard to t-stm and turbulence. Also arrival into busy a/p with high volumes of traffic getting vectored around wx and each other.
**C:** Avoiding wx cells (imbedded t-stm) when the wx radar is atenuating
**C:** Determine the level of turbulence and area boundaries.
**C:** Obtaining realtime data.

*Please rank order ( 1 = worst, 12 = least) the following ten weather hazards shown in table 6-3 on both frequency of encounter and consequences of encounter.*

## Table 6-3 Weather Hazards

| Frequency | | Consequence | |
|---|---|---|---|
| 1 | Convective Activity (including tornado, etc.) | 1 | Convective Activity (including tornado, etc.) |
| 2 | Other Turbulence | 2 | Microbust/Gust Front |
| 3 | Weather as a Ground Hazard (e.g., runway icing, RVR) | 3 | Low-Level Wind Shear (non-convective) |
| 4 | CAT (high altitude) | 4 | Weather as a Ground Hazard (e.g., runway icing, RVR) |
| 5 | Icing and Freezing Level | 5 | CAT (high altitude) |
| 6 | Low-Level Wind S hear (non-convective) | 6 | Volcanic Ash |
| 7 | Microburst/Gust Front | 7 | Lightning |
| 8 | Lightning | 8 | Other Turbulence |
| 9 | Widespread Low Visibility Inflight | 9 | Wake Vortex |
| 10 | Wake Vortex | 10 | Icing and Freezing Level |
| 11 | Volcanic Ash | 11 | Widespread Low Visibility Inflight |
| 12 | High Ozone Concentration | 12 | High Ozone Concentration |

There were 17 post-test usability questions that subjects completed evaluating screen effectiveness, terminology, system functionality, and intuitiveness. An example is provided below in Figure 6-10.

**Screen Effectiveness**

Visual Organization/ Page Layout

ineffective ←→ effective

1 2 3 4 5 6 7

Comments/ Suggestions:

**Figure 6-10 Sample usability question**

Subjects would circle a number 1(poor) through 7(excellent) that would correspond with their element rating. A list of usability categories and questions with overall subject mean scores is provided below in Table 6-4.

**Table 6-4 Mean Usability Scores**

| Screen Effectiveness | 4.8 | Terminology | 5.1 | System Functionality | 4.8 | Intuitiveness | 5.1 |
|---|---|---|---|---|---|---|---|
| Visual Organization/ Page Layout | 5.1 | Consistency of Terminology | 5.4 | Ease in Completing Weather-Constrained Flightplanning Tasks | 3.4 | Ease of Learning | 5.7 |
| Formats of dialog boxes including labels, titles, text, and data entry fields | 4.5 | Informativeness of Headers/ Labels | 5.2 | Time to Complete Weather-Constrained Flightplanning Tasks | 4.8 | Use of External Help | 4.2 |
| Visual Representations of Weather Hazards | 4.7 | Feedback to Operator Inputs | 4.8 | Ability to See Mistakes | 4.6 | Understanding temporal aspect of display | 5.2 |
| | | Error Indications | 4.8 | Ability to Correct Mistakes | 4.9 | Understanding Limitations (e.g., spatial and/or temporal uncertainty) of Data | 5.3 |
| | | | | Usefulness of Hazard Codes ($ ! * d) | 4.9 | Ability to Remember the Meaning of Hazard Codes ($ ! * d) | 5.3 |

Subjects were asked to check boxes corresponding to aspects of the testing environment. Figure 6-11 provides a sample testing environment question.

Please check the appropriate box to indicate aspects of the testing environment that may have influenced your performance and comment if applicable.

Initial instructions

☐ **Needs improvement** ☐ **poor** ☐ **fair** ☐ **good** ☐ **excellent**

**Figure 6-11 Sample Testing Environment Question**

The responses were tabulated and converted to numbers with 1 correlating to "needs improvement" and 5 meaning "excellent". Table 6-5 provides the mean testing environment scores.

### Table 6-5 Mean Testing Environment Scores

| | |
|---|---|
| initial instructions | 4.2 |
| realism and sufficient detail in scenarios | 3.7 |
| simulator test room environmental conditions | 3.9 |
| distractions in the lab | 4.2 |

We asked a question in the post-experiment questionnaire to try and gather information about the effectiveness of the polygons used in the AWIN tool to represent hazardous weather regions. The question and comments follow.

*Our current route optimizer prototype requires that weather hazard polygons be convex to simplify the calculations of what is "inside" or "outside" of a "no-fly" space. Do you think that this is too restrictive and that we should enhance the logic to accept all types of polygons? Also, we are looking for useful guidelines on approximate minimum size of the polygons (e.g., 30 miles minimum) and proximity (e.g., multiple small polygons, vs. concentric polygons, vs. large area polygons). Please comment in the space below.*

**D**: Logic needs to be enhanced -- upper fronts for example may be very narrow and clearly defined and could show as a straight line, not a polygon -- same with clear line of tstms. Also, size of polygon -- may want to enhance to delieate definite areas within polygon -- example, when major convective activity is _within_ the polygon area -- perhaps via color coding. also, how much of a buffer around actual wx phenomena is included in buffer -- is it actual area of wx or does it have a buffer zone around it (and if so, how much ?)
**A:** Polygons should be as accurate as possible. Size should depend on accuracy of information. No max or minimum size is necessary.
**A:** Divide into three levels: 1, enroute, 30 mile min, same polygon; 2, terminal, 10 mile min, more enhanced; 3, approach, 2 mile min, more enhanced.
**A:** Large polygons are restrictive. Smaller polygons minimum 50 miles perhaps may be acceptable, but generally weather hazards are large in size I.e., turbulence (100s of miles) or convection areas. You don't want to have too many waypoints on a route, especially a short leg and also if flying non-FMC aircraft i.e., manual 727, dc9, pilot workload would increase too much.
**C**: All types of polygons are needed if the flight planner is to be used in the terminal area for instance, planning a flight ito a destination on the backside of an occluded front or an ability to ignore individual hazards on a per flight basis. Minimum size depends on the type of hazard and how close a pilot is willing to fly to it, as well as the velocity of the phenomena and how often the system is updated (end user) for example a level 4-5 thunderstorm moving at 25 kts when the planners display is updated every 10 minutes. Minimum size needs to take the all into account.
**C:** Keep large areas, so the pilot can make his back-up plans.
**C:** The polygon shapes were good, not too restricitve. Miminum size would not be necessary. Just make them actual size. We can deal with facts.
**C:** The polygon is sufficient for the accuracy of the data that is presently available.

Subjects were asked to list their favorite and least favorite features for flight planning with their current flight planning system. The results of this question follow.

<u>Favorite</u>

**D:** Time and fuel burn accuracy
**D:** wx graphics -- that's it.
**A:** All automatic. Dispatch sends us the paperwork.
**C:** Currently, we call FSS for wx forecast and look at wx maps on WSI for flight planning.
**C**: Ease of use. With an input to 3 question a laterally optimized flightplan is produced. 2 more questions and it is filed with ATC.

Least Favorite

**D:** Mostly limited to fixed flight plan routes. Has limited random route capability.
**D:** Profile altitude selector, limits in ability for freeflight planning, lack of flexibility -- everything must be in database, if its not, then its difficult.
**D:** Lack of speed. Now computer memory is so limited because of all the 'add ins' to original system. Lack of flow of data -- very much a user unfriendly system.
**A:** Any changes I want to make must be coordinated with dispatch then new paperwork generated.
**A:** Dispatch has all the information. We rely on their expertise and the meteorology dept to attain the most reliable wx info and plan our flight for us. They do an excellent job, but pilots have little input until we are airborne.
**C:** No computer program are used, but we would like to have a program that produces a 'dispatch' type weather brief and preferred routing. Most imporantly, if it does not follow a direct line, pilot will need to know why before he/she will buy in and follow the routing.
**C:** Does not consider wx or wind.
**C:** Always goes to highest altitude, on short legs I.e., less than 250 miles it goes too high.

Subjects were asked to list their favorite and worst features for flight planning with the AWIN prototype flight planning system. The results of this question follow.

Favorite

**D:** Ease of flightplanning through areas of hazard establishing know parameters.
**D:** Overlay of turbulence, wx phenomenon
**D:** Depiction of three or m ore route choices
**D:** Visuals. Ease of enty of such things at adding fixes. Horizontal axis showing wx hazards. Speed. Turning world around on its axis. Graphic represntation of hazard altitudes.
**A:** The ability to move the aircraft into the future to see how weather hazard would impact your flight. Future look forward.
**A:** Easy to input hazards, and recaculate route.
**A:** Once identified the temporal ability was helpful
**A:** To see entire route with color coded hazards and view of flight profile with altitude slider
**C:** Depiction of entire route and associated hazards, time, and fuel analysis (cost analysis needed)
**C:** Visual graphics are great! Visual (big picture concept).
**C:** Graphicall depictions of routes and wx areas. Speed is good. Windows based with minimal keyboarding
**C:** Visual display. Ease of use.

Least Favorite

**D.** Routings do not reflect ATC constraints such as airways of track systems.
**D.** Changing data with moving aircraft.
**D.** Don't know system well enough.
**D.** None really -- it was pretty user friendly.
**A.** Difficult to see comparisons quickly while completing routes. Comparison.

**A.** Had to individually select each type of route. It should automtically calculate all 3.
**A.** Route entry: wp, ww, gc could all occur at the same time.
**A.** Having to click onto different parts to attain information e.e., hazard, route. Using arrow key not being 'click' to correct area.
**C.** Depiction of temporal effects on hazard movement
**C.** When comparing the three different flight routes for best time and fuel, click back and forth. I suggest a small table that shows all three at one time. Have some type of warning when fuel reaches landing mins.
**C.** Not all route comparisons time/fuel etc are shown on one page. Graphic display of routes need labels.
**C.** Would like to initially see 3 routes 1-great circle, 2-best time, 3-weather avoidance.

Subjects were asked if they had any suggestions to make flight planning with the AWIN prototype easier ? (e.g., additional functionality/ information to incorporate, better display formats, tools to help you make decisions with this data, etc.). Answers follow.

**D:** Add more flight planning parameters to flight and route planning box, such as alternate, reserve and contingency fuel, payload, etc. This will provide more realistic fuel burn and route selection.
**D:** Obviously such things as ATC restrictions, such as actual tracks and legal flight levels would need to be incorporated. Also such things as whether track can legally be used -- for example, certain tracks expire at certain times due to variety of reasons; -- flt planning system would definitely need to look at these parameters.
**A:** 1-Comparison window 2-Flight level changes 3- Different color for active route (like green on airbus)
**A:** Display result of each route sie-by-side (time, fuel burn, etc) put altitude parameters in the hazard box display.
**A:** Enhance temporal intuitiveness
**A:** Would have to use the system a bit more to answer. Got just enough practice/ experience on it to start feeling comfortable with it, but not enough to make a lot of suggestions.
**C:** Cost analysis, temporal effects on hazards, ability to change altitudes enroutes instead of rerouting around a hazard, inclusion of ETOPS requirement to ensure legality of flightplan include fuel planning and alternate destinations.
**C:** Time can be a factor when planning, I felt the speed of information was about right!
**C:** Table for flight route comparison. A quicker way to select all three types of routes on the first flight description/ definition page. Then the software could develop all three types of routing at once.
**C:** (1) Ability to file flightplan with ATC. (2) Provide TAFs and SAs for airport. ETOPS, ETP, etc.

## 7.0 References


1. *Weather Avoidance Using Route Optimization as a Decision Aid: An AWIN Topical Study*, Phase 1 Report, Honeywell Technology Center, Minneapolis, MN, December 30, 1998.

2. Palmer, M.T., Rogers, W.H., Press, H.N., Latorella, K.A., and Abbott, T.S. , *A Crew-Centered Flight Deck Design Philosophy for High-Speed Civil Transport (HSCT) Flight Deck Function,* NASA Contractor Report. Hampton, VA, NASA Langley Research Center, 1995.

# Appendices

## Proprietary Appendices (Separate Volume)

***Appendix F. Description of Three Dimensional Route Solver Algorithm***

***Appendix G. Route Solver Computer Program Structure***

***Appendix H. Constrained Altitude Cruise Optimization***